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# STABILIZING SIGNALS FOR SYSTEM STABILITY

by

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A THESIS

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## ABSTRACT

In modern power systems, the continuity of supply is of vital importance and, particularly where there are large blocks of remote generation, stability of the system under both transient and steady-state conditions is of great importance. Various means have been used to control or damp out oscillations occurring on the system due to interaction between electrical and mechanical characteristics of the machines and their prime movers. In recent years the emphasis has shifted to control of excitation using stabilizing signals in conjunction with static voltage regulators. The signals considered here are proportional to velocity and acceleration. The problem was examined on an analogue model and the results indicate that while velocity signals are effective and necessary, the use of an acceleration signal has merit, particularly for "first swing" control.

## ACKNOWLEDGEMENT

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# CHAPTER I

## INTRODUCTION

With power systems expanding in size and complexity and units of 500-1000 MW ratings being put in service, the problem of ensuring stability of the system assumes greater importance. System instability may result from power swings which arise as a consequence of either normal block load switching or from inadvertent conditions such as faults occurring on the system.

The excitation voltage of the generator is one parameter which can be used to improve the system stability. The advances in solid state devices have made practical the use of static excitation systems without the disadvantages of rotating exciters and having much faster response. In fact, in many cases, damping signals have been required to compensate the excitation system which has low or negative damping. Thus, with such systems, the possibility of recovery of the system from unstable conditions seems great. One must not conclude, however, that providing a fast-acting excitation system alone will improve stability. The improvement in stability performance of generators equipped with static excitation systems, depends upon many other factors such as,

1) Feed-back loop-gain and time constants of the control system,
2) Values of the transfer impedances between machines,
3) Load conditions of the system.

However, the above factors under operating conditions are fixed. Incorporating appropriate stabilizing signals in the voltage regulating feed-back loop is found necessary and if properly chosen, exhibits a definite improvement in the stability performance.

The effectiveness of a proportional velocity signal as a stabilizing signal having been established, there is a trend to incorporate this in the regulating circuits.

This study aims at examining the relative influence of other possible stabilizing signals such as proportional acceleration signal and proportional acceleration magnitude signal, on stability.

## Application of the Computer

The most convenient method to study the above problem is by simulation of a realistic model with its excitation system and voltage regulator on an analogue computer.

The conventional method of studying stability problems on network analysers has proven inadequate and time consuming. Most studies therefore, are now being undertaken on analogue and digital computers, each having its merits and demerits.

The analogue computer has the distinct advantage of easily representing the mathematical equations of the system and easily varying the system parameters, the greatest advantage being easy visualization of the changing conditions, most needed in such a study. The digital computer has on the other hand the overriding advantage of being able to cope with the large arrays of data and computation required for representation of even a small multimachine system.

In recent years many power utilities and manufacturers have carried out a variety of studies[1,2,3] of power system problems, both by digital and analogue methods.

## REVIEW OF THE LITERATURE

### Simulation

The simulation by Riaz[5] at MIT in 1956 aimed at a study of the voltage regulation problem of aircraft alternators. A more elaborate study was undertaken by Jean-Claude Roy[6] of Hydro-Quebec to analyse the effect of synchronous machine parameters on dynamic and transient stability. However, this study was on digital computer with the FACE multimachine programme developed by the General Electric Company. The system chosen for study was simple and the representation was further simplified by adopting certain approximations.

1) The variation of voltage due to variation in flux terms in the Park's equations were neglected.
2) The speed voltages were assumed constant, that is, the effect of frequency changes on these terms was assumed negligible.

The effect of other parameters such as adopting higher ceiling voltages, governor action and magnetic saturation have little effect on dynamic as well as transient stability. A further study by Smoliniski[7] on the same lines as undertaken by Roy established the need of accurate knowledge of various machine parameters and time constants for a detailed study.

Excitation System

Considerations in the design and selection of a particular excitation system suited to modern units appear in a number of publications recently.[2,4,8,9]

Voltage Regulators

Lye[9] has suggested the need for the voltage regulating system to incorporate certain special features essential for power systems operations such as

1) Reactive current compensation,

2) Manual follow-up facilities,

3) Joint var control for station generation on the same bus.

The above are the usual features necessary for conventional regulators also.

D.C. Sources

The problem associated with adopting static excitation systems needs special considerations and predetermination of

1) Overload ratings required of the excitation system,

2) Voltage regulation characteristics,

3) High voltage withstand requirements for direct connected rectifier transformers on generator terminals.

The problems of adopting various excitation systems incorporating the rectifiers, thyristers or silicon control rectifiers are dealt with successfully by the manufacturers.

Besides the above consideration, adopting a particular excitation system needs the examination of other application factors such as field flashing for initial start up by an external D.C. source.

Voltage Regulators and Stabilizing Signals

The voltage regulators in their simplest form have been represented by Roy[6] and Smolinski[7] by a transfer function having a single time constant. It is absolutely essential to have the stabilizing feed-back in the voltage regulator in the circuit. The system becomes unstable on larger swings or becomes oscillatory on smaller power swings when the signal is removed. The effects of the feed-back gain and the time constants of the stabilizing signal are distinct.

The effect of excitation control to improve power system stability studied by Schlief et.al.[11] is based on a simplified system representation. The results have established that the frequency deviation signal proves to be more effective than a proportional terminal voltage variation signal. Mason and Desrosiers[3] studied the effect of various stabilizing circuits on system stability during field tests and found integrating circuits more effective for stabilization than differentiating circuits. The gain of the stabilizing circuit, if optimised, damps the oscillations quickly. The integrating signal is equivalent to the rate of change of power angle. However, the above studies do not indicate the magnitudes of the load steps imposed on the system during field test.

In general, most studies make certain standard assumptions regarding speed voltages and rate of change of flux linkages. Those in which detailed stability analyses have been made have assumed linear relationships, that is, they study small disturbances, meaning studying dynamic stability.

This study considers a detailed analogue model considering changes in state flux linkages and speed voltages, as well as the non-linearities of the swing equation but considers only a single machine model connected to an infinite bus.

# CHAPTER II

## STABILITY CONSIDERATIONS

Stability when used with reference to a power system is "that attribute of the system, or part of the system, which enables it to develop restoring forces, between the elements thereof, equal to or greater than the disturbing forces so as to restore a state of equilibrium between the elements".[12]

The stability limit is "the maximum power flow possible through some particular point in the system when the entire system or part of the system to which the stability limit refers is operating with stability".[12] This definition applies to both steady state and transient conditions. Steady state stability limit refers to the maximum flow of power possible through a particular point without loss of stability when the power is increased very gradually. Transient stability limit refers to the maximum flow of power possible through a point without loss of stability when a sudden disturbance occurs.

The transient stability limit differs from the steady state stability limit because the former depends on the nature and severity of the disturbance and is always below the steady state stability limit. Because every system is subject to transient disturbances, transient stability is the more important of the two.

Another term commonly used is Dynamic Stability which is steady state stability with automatic voltage regulator.

The analysis of any power system to determine transient stability is essentially a combination of the analyses of the

electrical and mechanical systems. Under changed load conditions the rotor accelerates or decelerates due to the net effect of electrical torque and mechanical torque developed and has to adjust itself to the changed conditions of power transfer imposed. Therefore, the stability study implies study of system dynamics under changing conditions.

Swing Equation

The accelerating power torque on the rotor is the net difference in electrical and mechanical torque and is given by

$$T_a = T_m - T_e$$

where $T_m$ is the shaft torque or the mechanical input and $T_e$ is the electromagnetic torque developed in the rotor and $T_a$ is the output torque producing acceleration. Similarly the accelerating power is given by $P_a$

$$P_a = P_m - P_e \tag{1}$$

where $P_a$ is mechanical power input and $P_e$ is electrical power output. Also,

$$\begin{aligned} P_a &= T_a\omega \\ &= I\alpha\omega \\ &= M\alpha \end{aligned} \tag{2}$$

where the acceleration

$$\alpha = \frac{d^2\theta}{dt^2} \tag{3}$$

$\theta$, the angular displacement in radians is the total angle between the rotor axis at any instance from the reference axis

$$\theta = \omega_s t + \delta$$

Therefore

$$\frac{d\theta}{dt} = \omega_s + \frac{d\delta}{dt}$$

and

$$\frac{d^2\theta}{dt^2} = \frac{d^2\delta}{dt^2} \tag{4}$$

From equations (1) through (4)

$$M \frac{d^2\delta}{dt^2} = P_a = P_m - P_e \tag{5}$$

is the power swing equation[13] if it is assumed that there is no damping in the system. However, for all electromechanical systems there is some inherent damping always and it is justified to express (5) as,

$$M \frac{d^2\delta}{dt^2} + D \frac{d\theta}{dt} = P_m - P_e$$

or

$$M \frac{d^2\delta}{dt^2} + D_s\omega_s + D \frac{d\theta}{dt} = P_m - P_e \tag{6}$$

In equation (6) M is the momentum usually expressed in terms of the inertia constant H in the following manner.

$$H = \frac{\text{Stored energy in mega-joules (GH)}}{\text{Machine rating in MVA (G)}}$$

Also $\quad GH = \frac{1}{2} I\omega_o{}^2$

$$= \frac{1}{2} M\omega_o$$

Therefore,

$$M = \frac{2GH}{\omega_o}$$

$$= \frac{2H}{\omega_o} \text{ x (rating of machine in MVA)}$$

If the quantities are expressed in per unit quantities

$$M = \frac{2H}{\omega_o} \quad \text{per unit} \tag{7}$$

Substituting 7 in 6, we get the swing equation in the form

$$\frac{2H}{\omega_o} \frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_m - P_e \tag{8}$$

Equation 8 represents the dynamics of the system, with damping in which the constant torque $D_s\omega_s$ of equation 6 is included in $P_m$, leaving only $D\frac{d\delta}{dt}$ as velocity damping.

If the synchronous machine is connected through external reactance to an infinite bus, the equation for power output of the synchronous machine becomes

$$P_e = \frac{E\ e}{x_d + x_e} \sin\delta + \frac{e^2(x_d - x_q)}{2(x_d + x_e)(x_q + x_e)} \sin 2\delta \tag{9}$$

where $x_e$ = external reactance

$E$ = per unit field excitation voltage corresponding to the field excitation of the generator

$e$ = infinite bus voltage

The second term representing the reluctance power component is greatly reduced due to the introduction of external reactance.

For most practical problems, this term due to saliency is therefore neglected in calculating the power limit.

The maximum power is therefore given by

$$P_{max} = \frac{E\ e}{x_d + x_e} \sin 90°$$

and

$$P_e = P_{max} \sin\delta \tag{10}$$

Substituting 10 in the swing equation 8 we get

$$\frac{2H}{\omega_o} \frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_m - P_{max} \sin \delta \tag{11}$$

To study the dynamics of the system it is necessary to solve the differential equation (11). This can either be solved by a point method or can be studied on the analogue computer.

Even for the simple case of one machine tied on to the infinite bus with damping terms neglected, an analytical solution of (11) involves the use of elliptical integrals.

The stability under transient conditions can however, be determined without solving the swing equation by Equal Area Criterion of stability.

Criterion for Stability

The simplified form of the swing equation is

$$M \frac{d^2\delta}{dt^2} = P_m - P_e$$

multiplying both sides by $\frac{d\delta}{dt}$

$$M \frac{d^2\delta}{dt^2} \frac{d\delta}{dt} = (P_m - P_e) \frac{d\delta}{dt}$$

or

$$\frac{1}{2} M \frac{d}{dt} \left(\frac{d\delta}{dt}\right)^2 = (P_m - P_e) \frac{d\delta}{dt}$$

Therefore

$$\frac{d\delta}{dt} = \sqrt{\int_{\delta_o}^{\delta} \frac{2(P_m - P_e)}{M} d\delta} \tag{12}$$

where $\delta_o$ is the rotor angle under steady state operating conditions when

$$\frac{d\delta}{dt} = 0$$

After the disturbance the rotor adjusts itself at the changed rotor angle when $\frac{d\delta}{dt} = 0$. However, the machine does not come to the operating condition in the first excursion, but travels past this point due to the kinetic energy and reaches a point corresponding to $\delta_m$. On the first swing this is the point where $\frac{d\delta}{dt} = 0$. Therefore, at this point

$$\int_{\delta_o}^{\delta_m} \frac{2(P_m - P_e)}{M} \, d\delta = 0 \qquad (13)$$

The fact that $\delta$ has momentarily stopped at $\delta_m$ may be taken to indicate stability. This corresponds to saying that "the swing curve indicates stability when the angle $\delta$ reaches a maximum and starts to decrease on the basis that future peaks will not be higher than this peak".

This is the criterion for stability. The same is depicted by the equal area criterion.

<u>Equal Area Criterion</u>

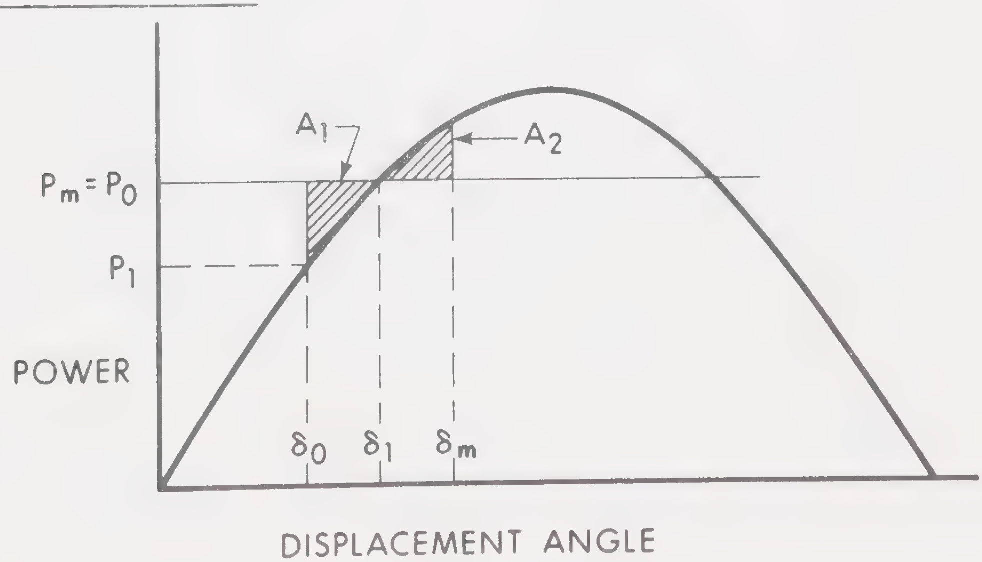


Fig. 1

Power-angle curve

If $P_o$ was the initial operating point where the electrical and mechanical torques are balanced and if the load is thrown off such that the electrical output corresponds to $P_1$ the difference of the mechanical and electrical torques will give accelerating torque to the rotor. Under this changed condition the area indicated by $A_1$ corresponds to the stored energy and given by

$$A_1 = \int_{\delta_o}^{\delta_1} (P_m - P_1)\, d\delta$$

If the machine swings past $\delta_1$ up to $\delta_m$ the area $A_2$ corresponding to the dissipated energy is given by

$$A_2 = \int_{\delta_1}^{\delta_m} (P_1 - P_m)\, d\delta$$

Then

$$A_1 - A_2 = \int_{\delta_o}^{\delta_1} (P_m - P_1)\, d\delta - \int_{\delta_1}^{\delta_m} (P_1 - P_m)\, d\delta$$

That is,

$$A_1 - A_2 = \int_{\delta_o}^{\delta_m} (P_m - P_1)\, d\delta \qquad (14)$$

For stability it is required that equation 14 is identically equal to zero, which means

Area $A_1$ = Area $A_2$

or

$$\int_{\delta_o}^{\delta_1} (P_m - P_1)\, d\delta = \int_{\delta_1}^{\delta_m} (P_1 - P_m)\, d\delta$$

or

$$\int_{\delta_o}^{\delta_1} 2(P_m - P_1)\, d\delta = 0$$

From the power angle diagram it is obvious that any analysis based on the Equal Area Criterion has to take into account the non-linear relation between output and displacement angle.

Effect of Inertia on Stability

To study the effect of any parameter on the stability performance it is necessary to have the analytical solution of the swing equation.

As already mentioned an analytical solution of the equation with all its non-linearities is not easily determinable. We can, however, try for one with certain assumptions, such as (i) for small oscillations the output varies linearly with the displacement angle and (ii) that the input and flux linkages are constant.

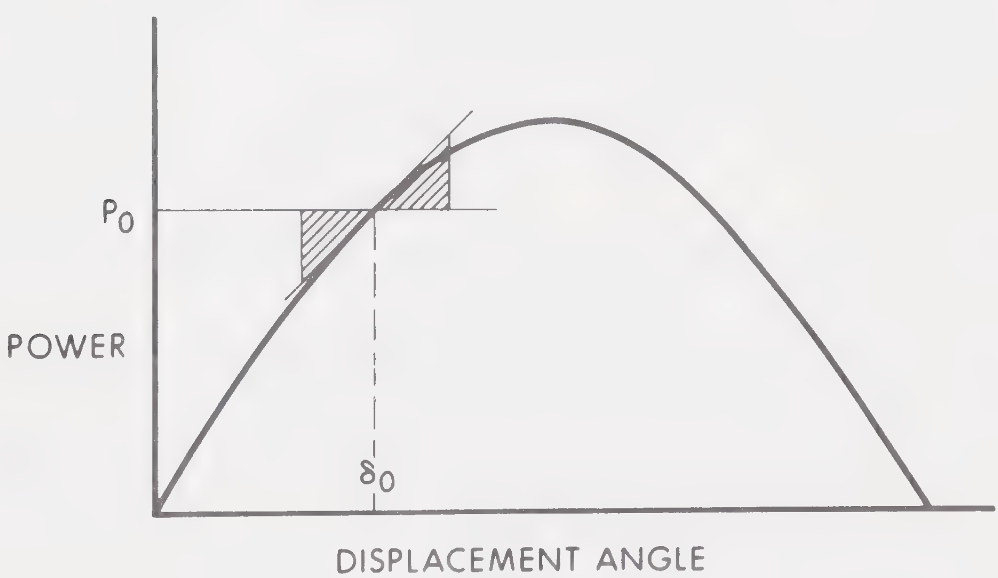


Fig. 2

Assuming linear relation between power displacement angle around operating point for a small disturbance.

Let $P = p\delta + b$ be the equation of the straight line portion placed at the operating point of the power angle curve where,

$$b = P_o - p\delta_o$$

and

$$P_o = \frac{E\ e}{z_1} \sin \delta$$

$$\frac{d^2\delta}{dt^2} = \frac{P_m - P}{M}$$

Substituting for P

$$\frac{d^2\delta}{dt^2} = \frac{P_m - p\delta - b}{M}$$

$$= \frac{P_m - b}{M} - \frac{p}{M}\delta$$

or

$$\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2 = 2\left(\frac{P_m - b}{M} - \frac{p}{M}\delta\right) d\delta$$

Therefore,

$$\frac{d\delta}{dt} = \sqrt{\frac{2(P_m - b)}{M} - \frac{p}{M}\delta^2 + \frac{c_1}{M}}$$

Separating variables and integrating results in,

$$\sin^{-1} \frac{p\delta - P_m - b}{\sqrt{(P_m - b)^2 + pc_1}} = \sqrt{\frac{p}{M}}\, t + c_2$$

which when solved for the angle $\delta$ gives,

$$\delta = \frac{P_m - b}{p} + \sqrt{\frac{(P_m - b)^2}{p^2} + \frac{c_1}{p}} \sin \left(\sqrt{\frac{p}{M}}\, t + c_2\right) \quad (15)$$

Evaluating $c_1$ and $c_2$ from initial conditions gives,

$$\delta = \frac{P_m - b}{p} - \left(\frac{P_m - b}{p} - \delta_o\right) \cos\sqrt{\frac{p}{M}}\, t \quad (16)$$

This equation indicates that if such a linear relationship between output and rotor displacement angle is assumed;

1) The oscillations are sinusoidal with respect to time.
2) The amplitudes are directly proportional to the initial power differential but entirely independent of the inertia of the machine.
3) The period of oscillation is affected by inertia and is proportional to the square root of the inertia constant.

The validity of the results of the linearized swing equation is seen from the power angle response curve obtained in fig. (3) where a small power disturbance was imposed on the system.

For larger excursions, because of the non-linear relationship between output and displacement, a conclusion of the above nature is not justified. Actual computer studies show that the amplitude depends on inertia in these cases and is indicated in fig. (4).

For transient stability, in order to fulfil the equal area criterion any measure which can raise the $p_{max}$ or equalise the positive and negative energy areas $A_1$ and $A_2$ is desirable. The latter was achieved to a great extent by adopting fast relaying systems and circuit breakers.

To insure transient stability under large power oscillations (even beyond the limit attainable by adopting fast relays and circuit breakers) any measure which modifies the power angle curve and raises the stability limit is most desirable.

Excitation control, by modifying E can influence stability. Until the development of modern excitation systems with field forcing,

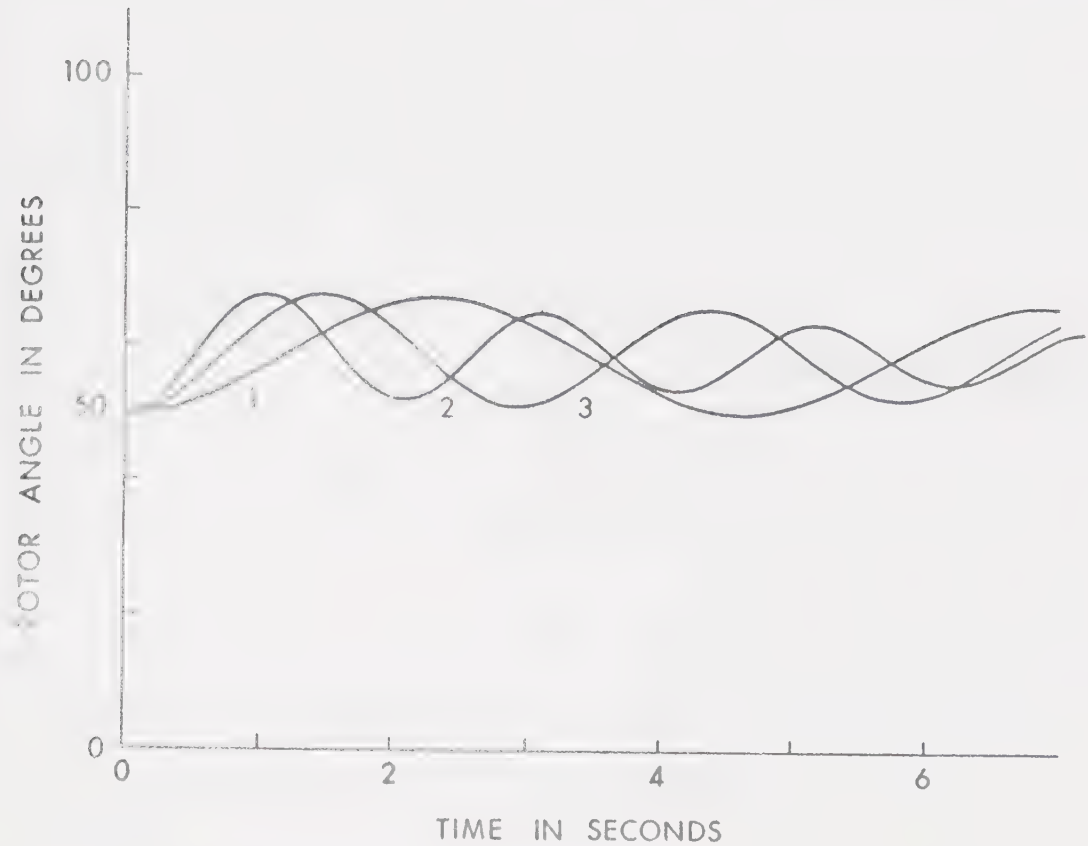


Fig. 3

System Response after Small Power Disturbance

(1) with H = 6

(2) with H = 1.5

(3) with H = 3

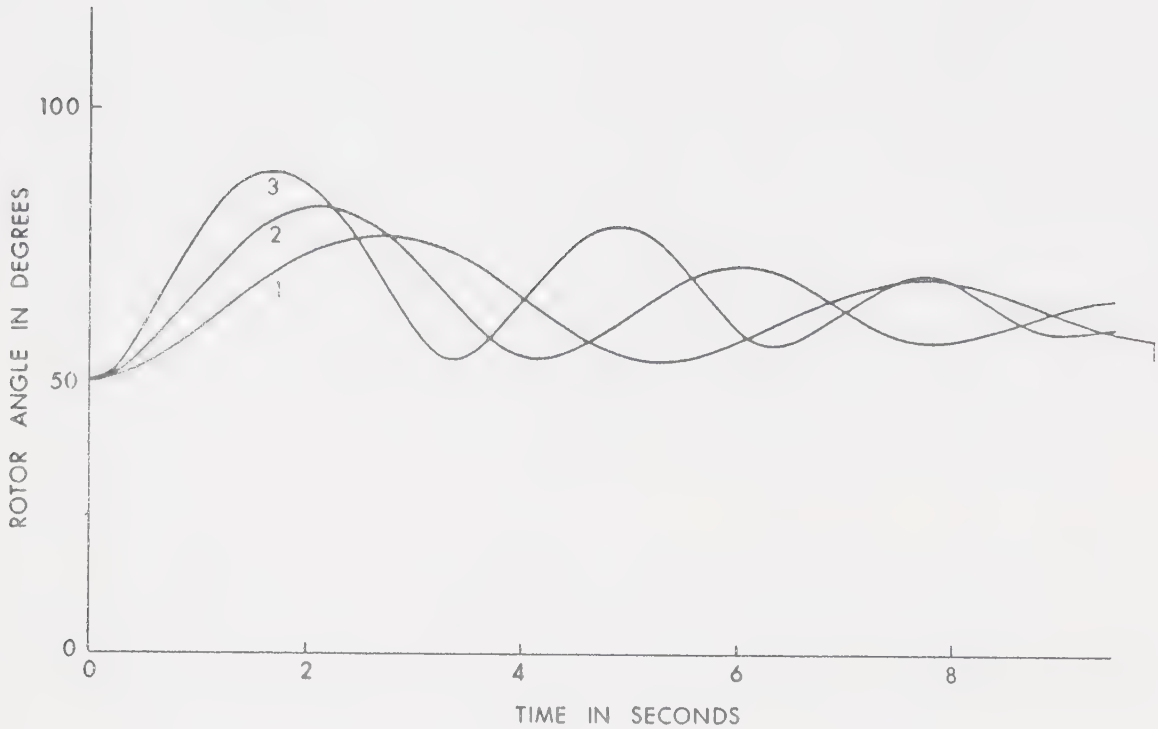


Fig. 4

System Response after Large Power Disturbance

(1) with H = 6

(2) with H = 3

(3) with H = 1.5

this possibility could not be taken advantage of because of the response times involved.

# CHAPTER III

## STATIC EXCITATION SYSTEM AND STABILIZING CIRCUIT CONSIDERATIONS

Static excitation systems are now competitive in cost to conventional rotating exciters for ordinary applications where there is no stability problem. There are also applications where transient stability is not a problem but dynamic stability is. Neither of these applications require ceiling voltages above the normal level of 3.0 to 3.5 per unit. The only limitation in the choice of static excitation system is the thermal capacity, and this is a major consideration in cases where high current capacity is required even for a short time.

The major advantages of a static excitation system are the faster response and the elimination of commutation problems. Faster response directly improves the transient and dynamic stability.

### Static Excitation with no Stabilizing Signal

Such a regulator is very effective in controlling voltage as desired but can contribute to dynamic instability as has been found in practice by Ontario Hydro and other utilities. This is due to the fact that such a regulator may effectively introduce negative damping so that small normal system disturbances lead to growing oscillations in displacement angle and eventual loss of system stability. A small speed signal is sufficient to provide the necessary damping. For smaller disturbances the damper windings

alone may be sufficient to damp out these oscillations.

A common disturbance involves loss of transmission capability and a corresponding loss of load. This leads to an increase in machine speed and an increase in terminal voltage. The voltage regulator is such as to reduce voltage and hence reduce output, increasing the acceleration. This is exactly the wrong action making the system less stable as depicted by the figure 5 below.

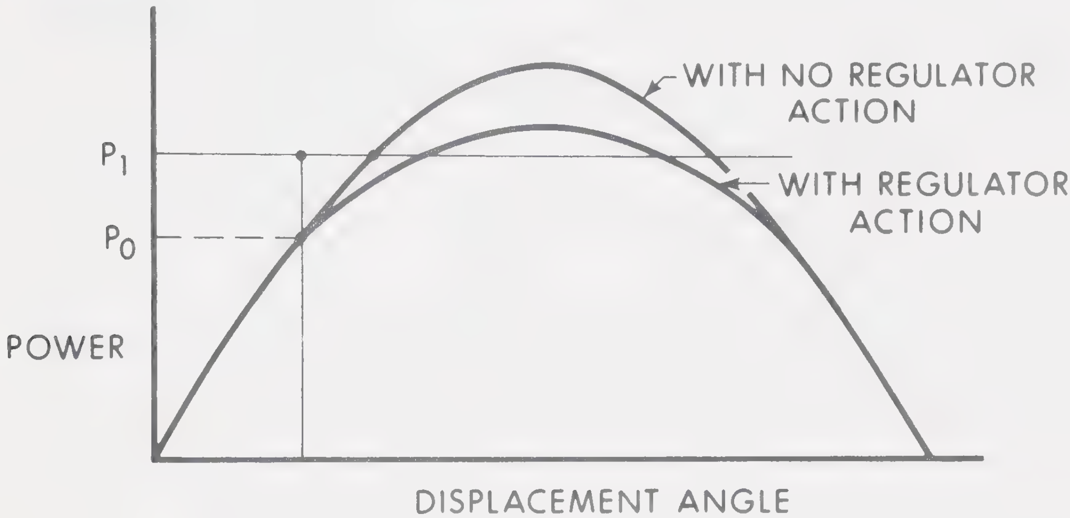


Fig. 5

Power Angle Diagrams Showing Wrong
Voltage Regulator Action

Hence, where static excitation, with fast response is used, the following signals are needed:

1) Some damping for control of dynamic (small signal) stability
2) Stabilizing signals to improve transient stability.

The former problem is relatively simple as a linear model can be used for analysis but in the second case non-linearities add difficulties.

Existing studies have considered the linearised or small disturbance model only but have in some cases extended their conclusions to large disturbances where the validity of the model is doubtful. While (small disturbance) dynamic stability must always be maintained, the control of transient stability (first swing) does not necessarily follow.

Stabilizing Signals

1) Velocity - a signal proportional to $\frac{d\delta}{dt}$ or the integral of the accelerating power provides damping

$$M \frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_i - P_e$$

and hence always stabilizes in the linear case and reduces the amplitude of the swing. Such a signal may not be most effective on the first swing.

2) Acceleration - a signal proportion to rotor acceleration can reduce the first swing by effectively modifying M but may effectively reduce damping increasing the danger of dynamic instability.

$$M \frac{d^2\delta}{dt^2} = P_i - P_{e_o}(\delta) - \left(\frac{d^2\delta}{dt^2}\right) P_e'(\delta)$$

$$\frac{d^2\delta}{dt^2} = \frac{P_i - P_{e_o}}{M + P_e'}$$

If $P_e'$ was constant this signal would affect the period of oscillation only but $P_e'$ is most effective near 90° so that the signal affects the magnitude of the swing.

3) Acceleration Magnitude - if the magnitude of the acceleration is used, the inertia may be effectively increased when $\frac{d^2\delta}{dt^2} > 0$ and reduced when $\frac{d^2\delta}{dt^2} < 0$ in the case of loss of load. Note that in this case the action is to increase voltage, improving stability. This signal is effective in reducing the first swing peak but with low damping can lead to dynamic instability. Hence, some damping is required. Also such a signal may need logic control to decide the sign of the signal depending on loss or gain of load.

This paper thus studies the effectiveness of these various signals and attempts to point out possible combinations which would be useful.

# CHAPTER IV

# SIMULATION

Stability study of a system on analogue computers requires simulation of the following:

1) Synchronous machine

2) Swing equation

3) Line and infinite bus

4) Voltage regulator with stabilizing signal.

## Machine and System

The system simulated on the analogue computer consists of a single machine connected to an infinite bus through a line impedance. The synchronous machine including its saliency is best represented by a mathematical model based on Park's equations[14] in direct and quadrature axis components. These completely describe the variations of flux and voltage produced in the stator and rotor circuits. The equations are summarised in the following manner, considering one set of damper windings on each axis.

$$\left.\begin{aligned} v_f &= r_f i_f + p\psi_f \\ v_d &= -r_a i_d + p\psi_d - \omega\psi_q \\ v_q &= -r_a i_q + p\psi_q + \omega\psi_d \\ v_{kd} &= 0 = r_{kd} i_{kd} + p\psi_{kd} \\ v_{kq} &= 0 = r_{kq} i_{kq} + p\psi_{kq} \end{aligned}\right\} \qquad (17)$$

which gives

$$p\psi_f = v_f - r_f i_f$$

$$\left.\begin{array}{lcl} p\psi_d & = & v_d + r_a i_d + \omega\psi_a \\ p\psi_q & = & v_q + r_a i_q - \omega\psi_d \\ p\psi_{kd} & = & - r_{kd} i_{kd} \\ p\psi_{kq} & = & - r_{kq} i_{kq} \end{array}\right\} \quad (18)$$

where the flux ($\psi$) terms are given by the following equations

$$\psi_f = \psi_{md} + \psi_{f1} = \frac{1}{\omega_o}\ [(x_{md} + x_{f1}) i_f - x_{md} i_d + x_{md} i_{kd}]$$

$$\psi_d = \psi_{md} + \psi_{d1} = \frac{1}{\omega_o}\ [x_{md} i_f - (x_{md} + x_{a1}) i_d + x_{md} i_{kd}]$$

$$\psi_q = \psi_{mq} + \psi_{q1} = \frac{1}{\omega_o}\ [-(x_{mq} + x_{a1}) i_q + x_{mq} i_{kq}] \quad (19)$$

$$\psi_{kd} = \psi_{md} + \psi_{kd1} = \frac{1}{\omega_o}\ [x_{md} i_f - x_{md} i_d + (x_{md} + x_{kd1}) i_{kd}]$$

$$\psi_{kq} = \psi_{mq} + \psi_{kq1} = \frac{1}{\omega_o}\ [-x_{mq} i_q + (x_{mq} + x_{kq1}) i_{kq}]$$

we substitute the following in the above equation

$$\begin{array}{l} x_f = x_{md} + x_{f1} \\ x_d = x_{md} + x_{a1} \\ x_q = x_{mq} + x_{a1} \\ x_{kd} = x_{md} + x_{kd1} \\ x_{kq} = x_{mq} + x_{kq1} \end{array} \quad (20)$$

also

$x_{md} = x_{mf} = x_{mkd} = x_{fd} = x_{fkd} = x_{kdd} = x_{ad}$ the per unit direct axis mutual reactance, and

$x_{mq} = x_{mkq} = x_{kqq} = x_{aq}$ the per unit quadrature axis mutual reactance. As all the direct axis mutual reactances are equal and all the quadrature axis mutual reactances are equal the equation (19), then can be written in the matrix form:

$$\begin{bmatrix} \psi_f \\ \psi_d \\ \psi_{kd} \\ \psi_q \\ \psi_{kq} \end{bmatrix} = \frac{1}{\omega_o} \begin{bmatrix} x_f & -x_{ad} & x_{ad} & o & o \\ x_{ad} & -x_d & x_{ad} & o & o \\ x_{ad} & -x_{ad} & x_{kd} & o & o \\ o & o & o & -x_q & x_{aq} \\ o & o & o & -x_{aq} & x_{kq} \end{bmatrix} \begin{bmatrix} i_f \\ i_d \\ i_{kd} \\ i_q \\ i_{kq} \end{bmatrix} \qquad (21)$$

Equation (21) is rewritten in terms of current quantities

$$\begin{bmatrix} i_f \\ i_d \\ i_{kd} \\ i_q \\ i_{kq} \end{bmatrix} = \omega_o \begin{bmatrix} x_f & -x_{ad} & x_{ad} & o & o \\ x_{ad} & -x_d & x_{ad} & o & o \\ x_{ad} & -x_{ad} & x_{kd} & o & o \\ o & o & o & -x_q & x_{aq} \\ o & o & o & -x_{aq} & x_{kq} \end{bmatrix}^{-1} \begin{bmatrix} \psi_f \\ \psi_d \\ \psi_{kd} \\ \psi_q \\ \psi_{kq} \end{bmatrix} \qquad (22)$$

Equations (21) and (22) completely represent the interaction of flux and voltage in the synchronous machine and are the basic equations for simulation on the Analogue Computer.

The effect of saturation has been ignored.

## Swing Equation

The dynamics of the machine are well represented by the power equation

$$M \frac{d^2\delta}{dt^2} + D \frac{d\delta}{dt} = P_m - P_e$$

or

$$\frac{2H}{\omega_o} \frac{d^2\delta}{dt^2} + D \frac{d\delta}{dt} = P_m - P_e$$

where $P_e^{(15)}$ the electrical power output is given by

$$P_e = (i_q \psi_d - i_d \psi_q)\,\omega$$

Line and Infinite Bus

The machine is tied on its machine bus where we measure the terminal voltage $v_t$ the power output $P_e$ and the overall rotor angle displacement $\delta$. The tie between the machine bus and the infinite bus consists of the line impedance (in this case it is taken to be a reactive tie) where the desired bus voltage e equal to 1 per unit is maintained.

The direct and quadrature axis components of the terminal voltage are given by

$$v_d = i_d r_L - x_L i_q + e \sin \delta$$

$$v_q = i_q r_L + x_L i_d + e \cos \delta$$

$$v_t = \sqrt{v_d^{\,2} + v_q^{\,2}}$$

The values of parameters to represent a realistic machine model were taken from those of reference 6 and are separately given in Appendix I.

The scaled equations are given in Appendix II.

Voltage Regulator

The voltage regulator in its simplest form for simulation is given in fig. AII-4, where

$$\frac{\Delta v_f}{\Delta v_r} = \frac{k_E}{T_E s + 1}$$

where $T_E$ is the exciter time constant and $k_E$ the voltage regulator

loop gain.

If the stabilizing signal is proportional to the velocity error it can be taken as

$$\Delta v_{\omega} = \frac{k_1}{(T_1 s + 1)} \Delta P_e$$

while a signal proportional to acceleration that is, proportional to power differential is simply

$$\Delta v_a = k_2 \Delta P$$

To study the effects of various signal gains on the system performance, the simplest form of regulator was simulated.

As is evident from the figure an overall transfer function is difficult to calculate because of the machine transfer function and the non-linearities as represented in the voltage regulator circuit.

The Analogue Computer diagrams are given in fig. AII-1,2,3,4 in Appendix II.

# CHAPTER V

## RESULTS

The effects of proportional velocity, acceleration and acceleration magnitude signals in the feedback-loop of the voltage regulator have been studied in the following tests.

The merits of the signals in improving stability performance are seen on small as well as large power disturbances.

Next, to obtain the maximum advantage of these signals, the effect of various combination signals is studied.

In the following tests a disturbance is simulated by raising the input power $P_m$ by an amount $\Delta P_m$ (proportional to loss in load) by closing a function switch on the analogue computer panel.

Large Power Disturbance

Test 1.

case (i) Steady state power output $P_e$ 1 per unit

Loss of load $\Delta P_m$ 1.6 per unit

Gain of stabilising signal 1 per unit

| $P_e$ | $\Delta P_m$ | Signal | Gain | Curve | Remarks |
|---|---|---|---|---|---|
| 1.0 | 1.6 | no. sig. | 0 | 1 | - |
| 1.0 | 1.6 | $\dot{\delta}$ | 1 | 2 | - |
| 1.0 | 1.6 | $\ddot{\delta}$ | 1 | 3 | - |
| 1.0 | 1.6 | $\lvert\ddot{\delta}\rvert$ | 1 | 4 | least unstable |

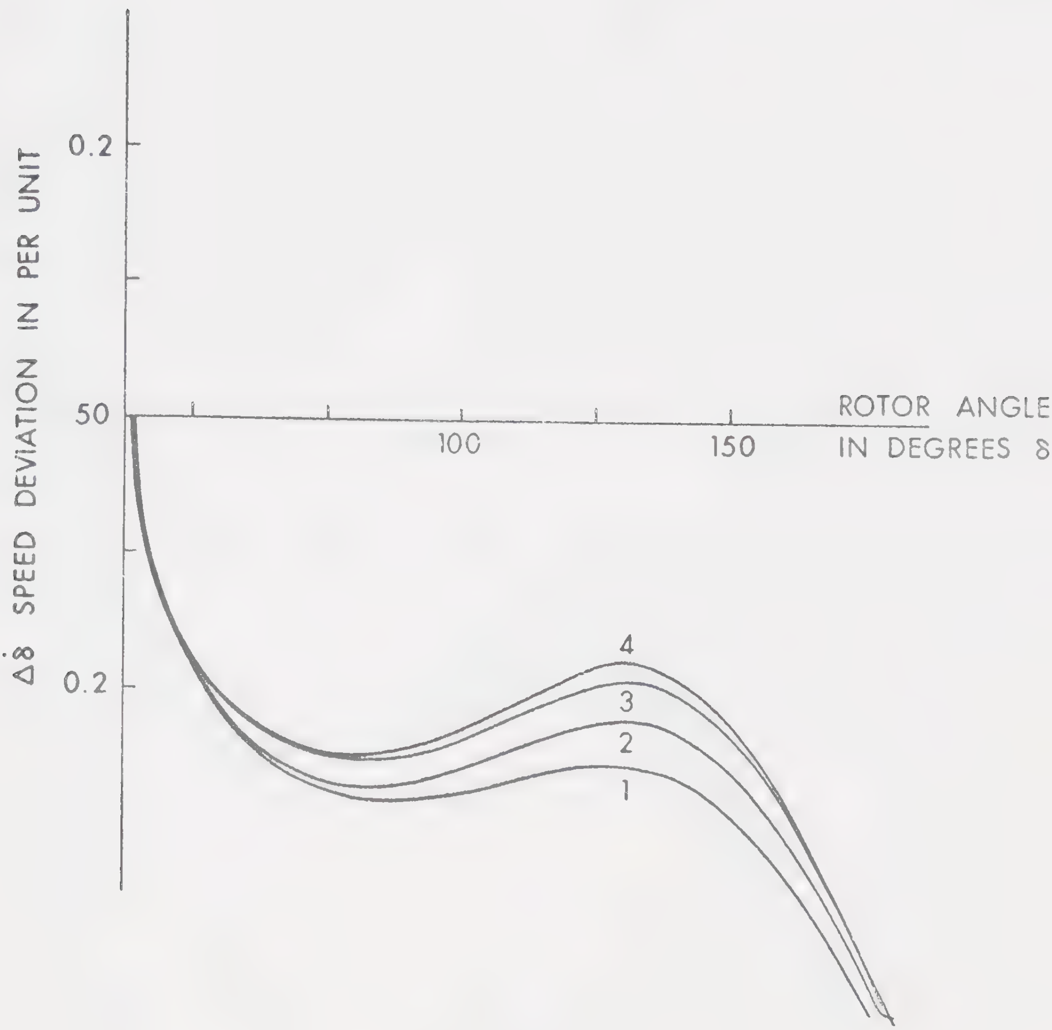


Fig. 6

Test 1 Case (i)

Relative Effect of Different Stabilizing Signals

Value of Gain 1.0

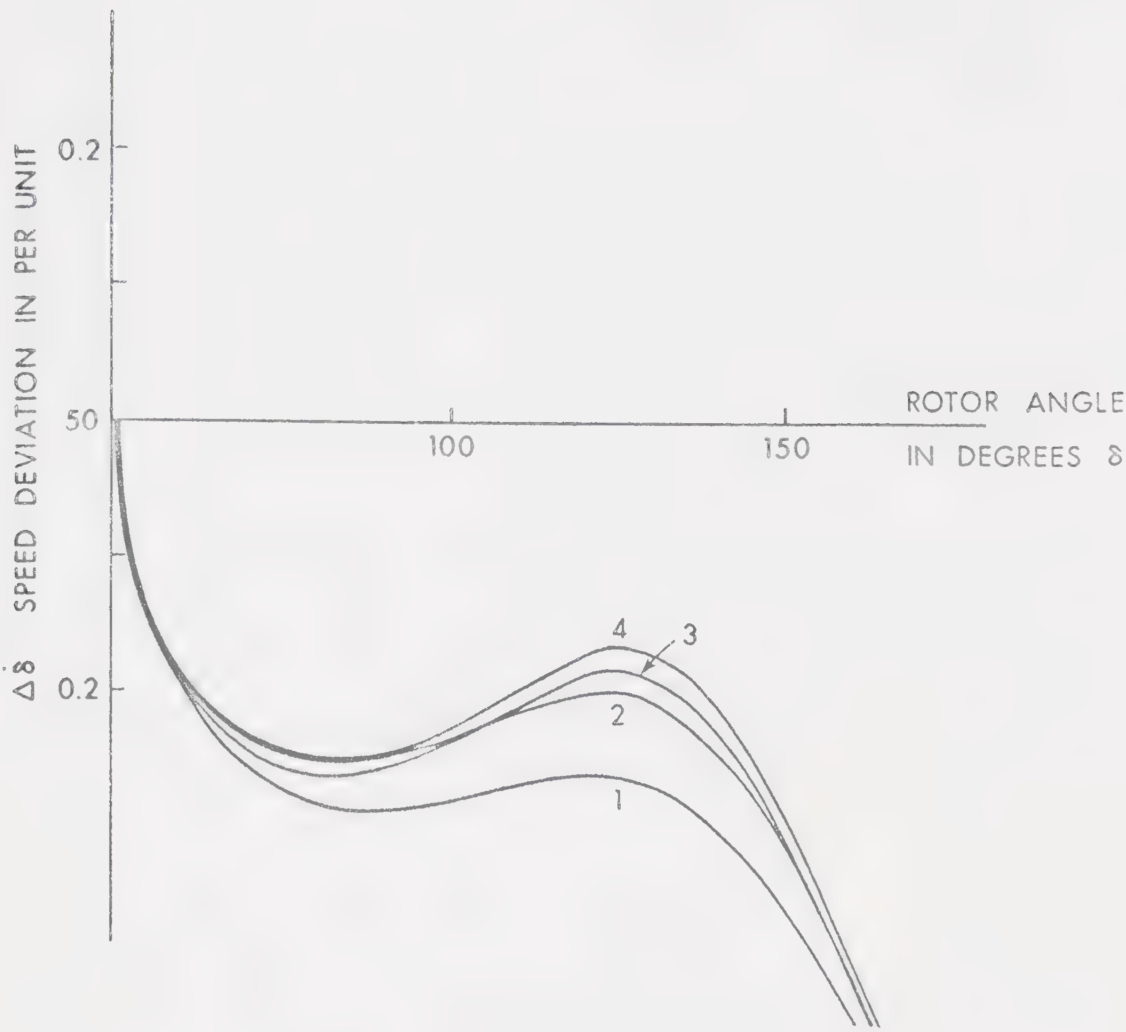


Fig. 7

Test 1 Case (ii)

Relative Effects of Different Stabilizing Signals

Value of Gain 2.0

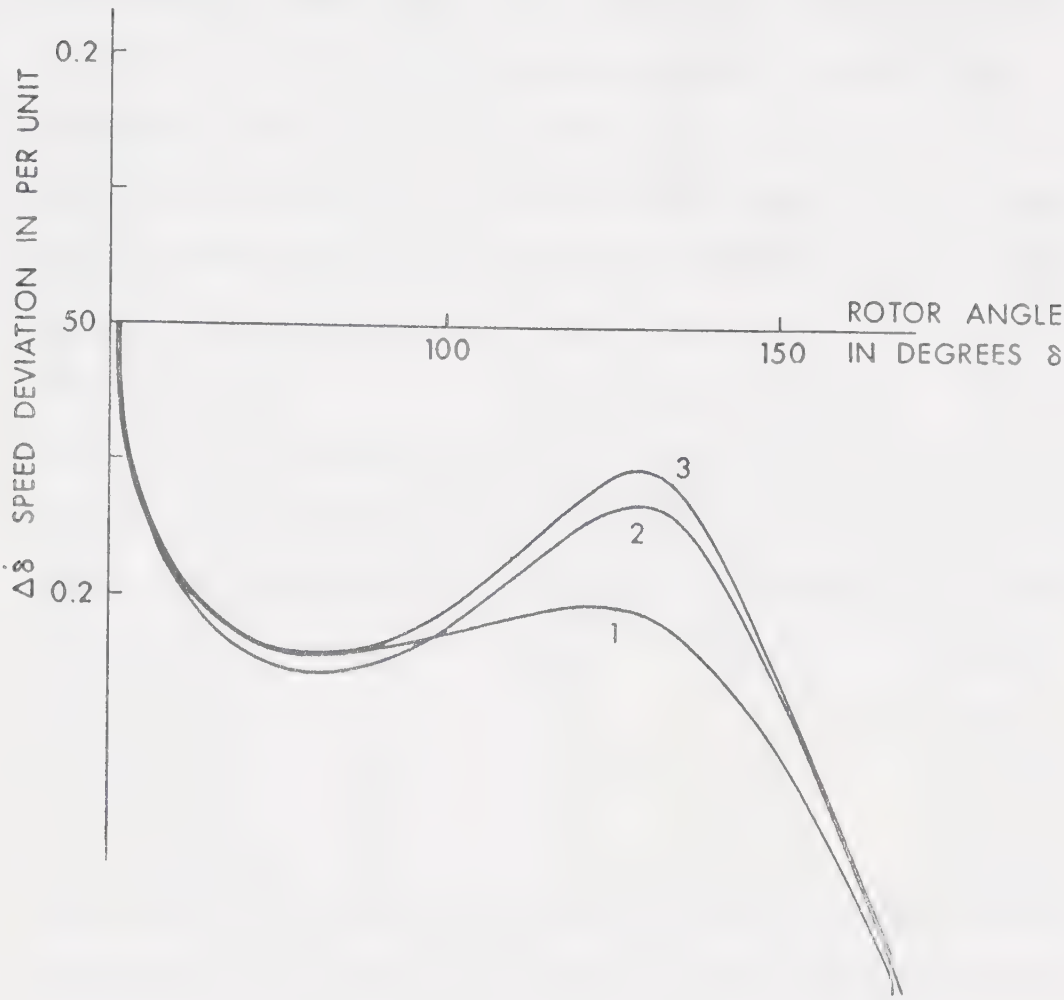


Fig. 8

Test 1 Case (iii)

Relative Effects of Different Stabilizing Signals

Value of Gain 5.0

The above test incorporated a small value of gain for the stabilising signal to observe the relative effectiveness in arresting the power angle swing. It is seen from fig. (6) that curve 4 due to acceleration magnitude signal gives the least deviation, though in all cases the system is unstable.

case (ii) The above test was repeated with larger values of gain and the same result as in case (i) were obtained which are given in figures 7 and 8.

Test 2.

case (i) The operating point on the power angle curve is changed. The electrical output is now 1.5 per unit, a large disturbance is imposed corresponding to 0.8 per unit and a higher gain is used.

| $P_e$ | $\Delta P_m$ | Signal | Gain | Curve | Remarks |
|---|---|---|---|---|---|
| 1.5 | 0.8 | $\lvert\ddot{\delta}\rvert$ | 5 | 1 | stable |
| 1.5 | 0.8 | $\dot{\delta}$ | 5 | 2 | unstable |
| 1.5 | 0.8 | $\ddot{\delta}$ | 5 | 3 | unstable |

This represents a case when the system on such a large disturbance inherently is unstable on the first swing but the acceleration magnitude signal is able to arrest the power swing, though its effect on the later oscillations is not predicted in this case (figure 9).

case (ii) Relative effects of the signals are next seen on the same disturbance with higher values of gain as given in figure (10).

| $P_e$ | $\Delta P_m$ | Signal | Gain | Curve | Remarks |
|---|---|---|---|---|---|
| 1.5 | 0.8 | $\lvert\ddot{\delta}\rvert$ | 9 | 1 | first peak 102° |
| 1.5 | 0.8 | $\dot{\delta}$ | 9 | 2 | first peak 112° |
| 1.5 | 0.8 | $\ddot{\delta}$ | 9 | 3 | unstable |

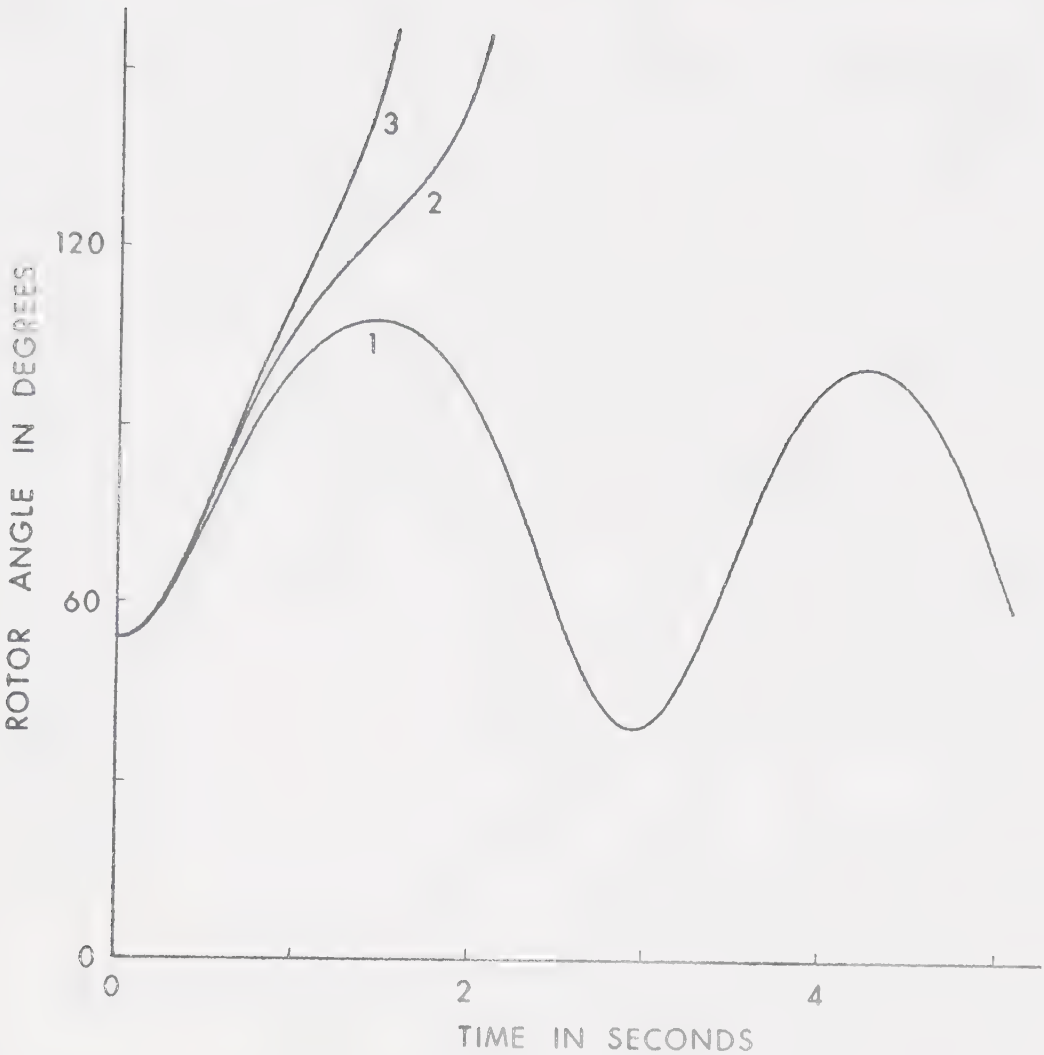


Fig. 9

Test 2 Case (i)

Effects of Different Stabilizing Signals on

Large Power Disturbance (0.8 p.u.)

1. with acceleration magnitude signal

2. with velocity signal

3. with acceleration signal

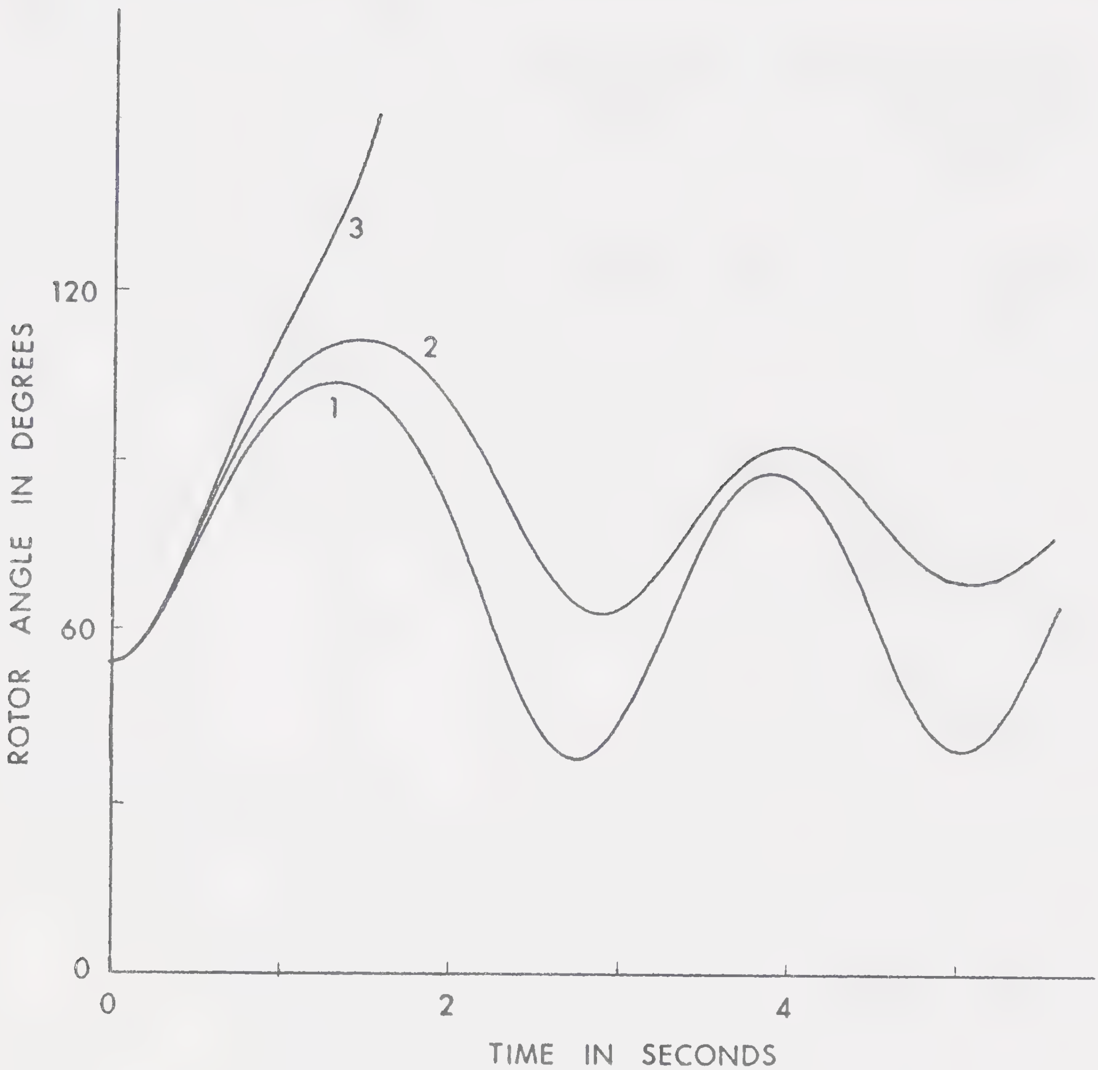


Fig. 10

Test 2 Case (ii)

Effects of Different Stabilizing Signals on

Large Power Disturbance

1. with acceleration magnitude signal

2. with velocity signal

3. with acceleration signal

The acceleration magnitude signal when compared with the velocity signal shows that

(i) on the first swing, acceleration magnitude signal gives a peak about 10% less than that obtained with the velocity signal.

(ii) the acceleration magnitude signal makes the system more oscillatory on subsequent swings than is the case with a velocity signal.

case (iii) The disturbance is reduced to 0.6 per unit.

| $P_e$ | $\Delta P_m$ | Signal | Gain | Curve | Remarks |
|---|---|---|---|---|---|
| 1.5 | 0.6 | $\lvert\ddot{\delta}\rvert$ | 9 | 1 | first peak 83° |
| 1.5 | 0.6 | $\dot{\delta}$ | 9 | 2 | first peak 88° |
| 1.5 | 0.6 | $\ddot{\delta}$ | 9 | 3 | first peak 97° |

It is seen (fig.11) that

(i) the acceleration magnitude signal gives the least value of first swing but makes the system more oscillatory on following swings compared to those obtained with the velocity signal.

(ii) the effect of the acceleration signal was not definitely determined in cases (i) and (ii). In this case it is able to arrest the first swing but builds up larger oscillations than those obtained with the other two signals.

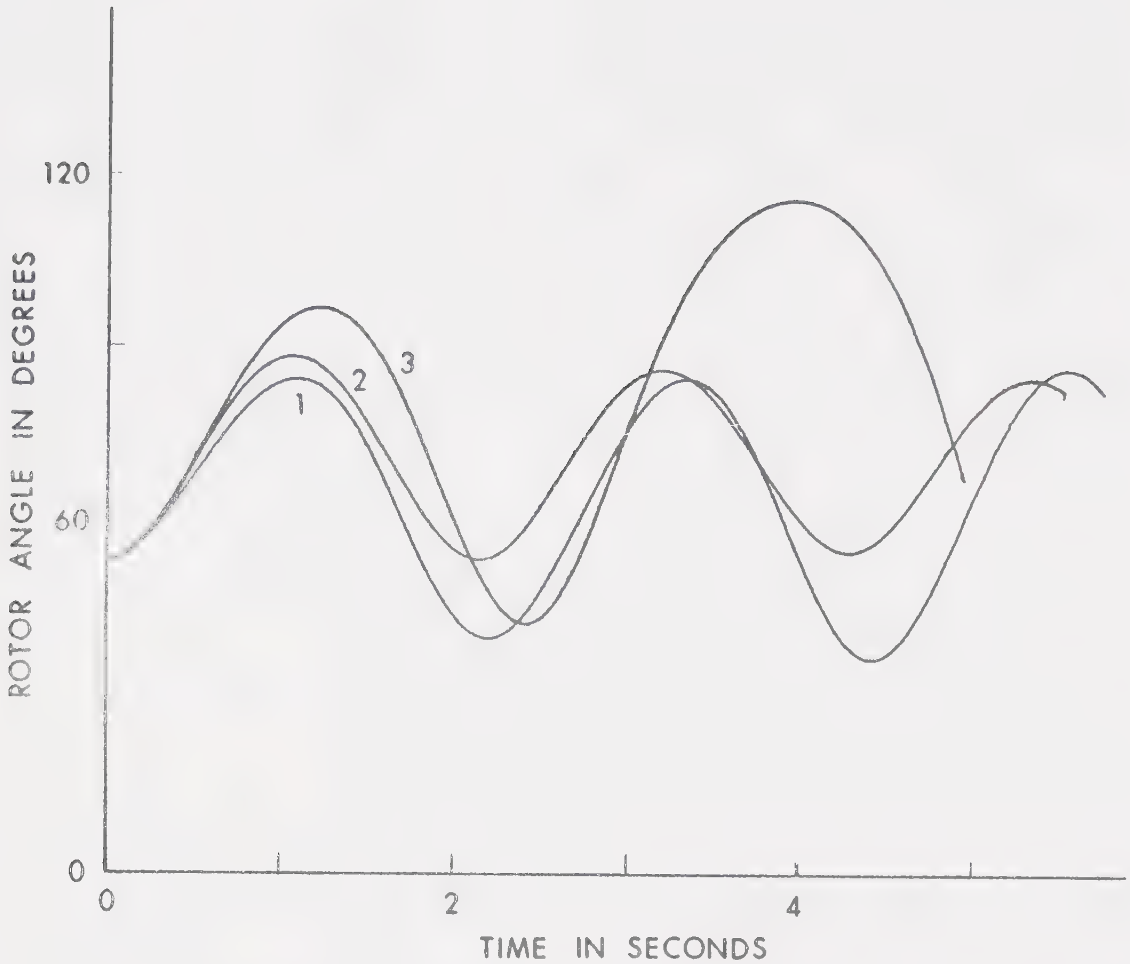


Fig. 11

Test 2 Case (iii)

Effects of Different Stabilizing Signals

Power Disturbance of 0.6 p.u.

1. with acceleration magnitude signal

2. with velocity signal

3. with acceleration signal

Test 3

The effect of the three signals is observed on a small power swing corresponding to loss of load of 0.4 per unit (fig. 12).

| $P_e$ | $\Delta P_m$ | Signal | Gain | Curve | Remarks |
|---|---|---|---|---|---|
| 1.5 | 0.4 | $\lvert\ddot{\delta}\rvert$ | 5 | 1 | first swing 70° |
| 1.5 | 0.4 | $\dot{\delta}$ | 5 | 2 | first swing 76° |
| 1.5 | 0.4 | $\ddot{\delta}$ | 5 | 3 | first swing 82° |
| 1.5 | 0.4 | nil | 5 | 4 | first swing 82° |

The case establishes that

(i) the acceleration magnitude signal is still more effective on first swing than other signals.

(ii) the acceleration signal does not affect first swing but builds up higher oscillations than occur without any signal.

(iii) the velocity signal is more effective on later swings.

Test 4

The feedback loop gain of the stabilizing signal has considerable influence on stability performance. This was demonstrated by this test and the results are given in figures 13, 14, and 15.

(i) Referring to figure 13 we find for this particular case of large power disturbance that the velocity signal with higher gain damps out the oscillations much faster. The gain was varied from 4 to 400. At the higher values the second peak starts getting prominent which very much affects the voltage regulation. A corresponding higher voltage appears

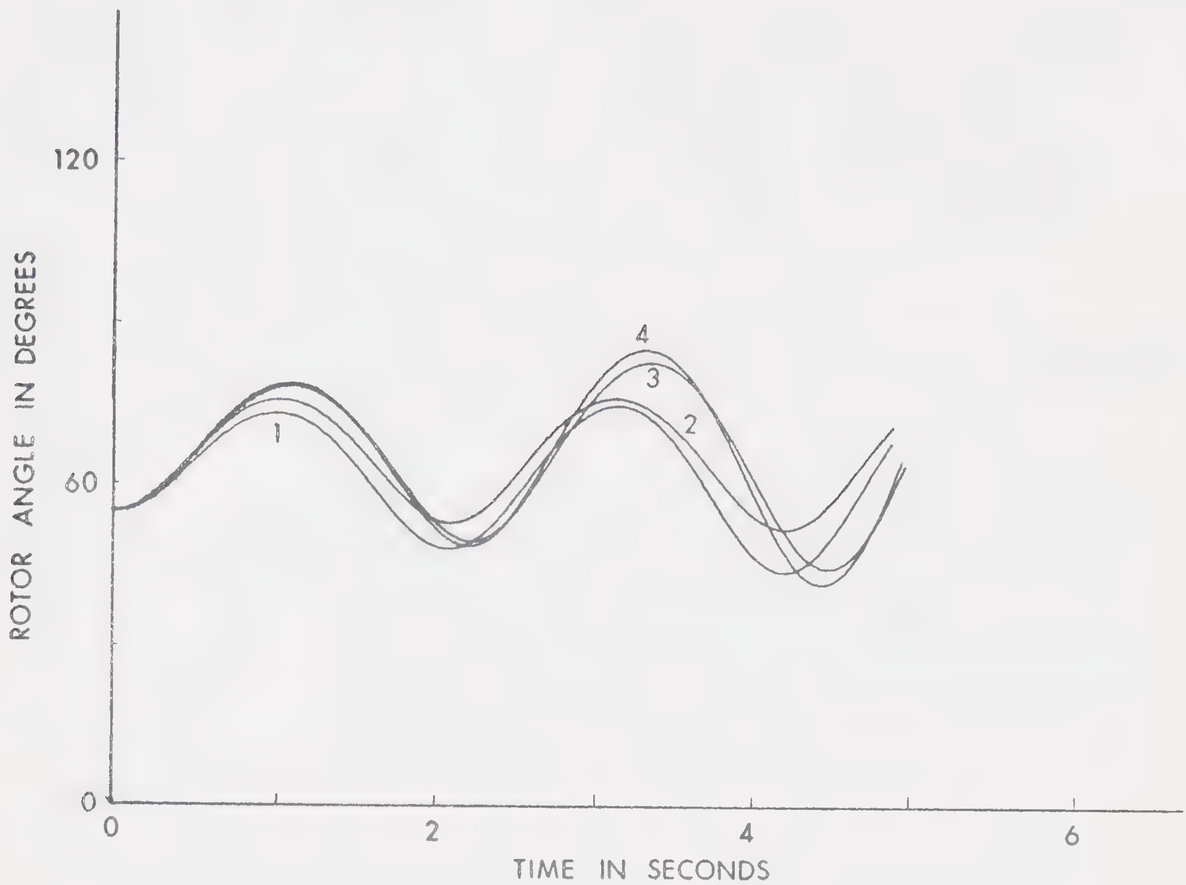


Fig. 12

Effect of Stabilizing Signals on Small

Power Disturbance 0.4 p.u.

(1) with acceleration magnitude signal

(2) with velocity signal

(3) with acceleration signal

(4) with no signal

on the second swing, which may not be acceptable.

(ii) The acceleration signal gain was increased up to 12. This tries to arrest the power excursion slightly but when the gain is increased above 12 the signal drives the system towards instability (figure 14).

(iii) The effect of gain in case of acceleration magnitude signal is quite prominent as is seen from the response curves in figure 15. The first swing is reduced with gains up to 100 but further increase in gain does not contribute appreciably thereafter. This is seen at gains of 130. If gain is further increased the system goes unstable.

Test 5

case (i) The test is aimed to find the effect of combination of signals and to see if the benefits of both the acceleration magnitude and velocity signal can be derived in case of a large disturbance. During test a number of combinations and switchings were tried to get the best results. The following is a typical case and is given in figure 16.

| $P_e$ | $\Delta P_m$ | Signal | Gain | Curve | Remarks |
|---|---|---|---|---|---|
| 1.5 | 0.8 | $\lvert\ddot{\delta}\rvert$ | 9 | 1 | first swing 102° |
| 1.5 | 0.8 | $\dot{\delta}$ | 9 | 2 | first swing 112° |
| 1.5 | 0.8 | $\lvert\ddot{\delta}\rvert$ / $\dot{\delta}$ | 9 | 3 | first swing 102° |

For the case represented by curve 3 the acceleration magnitude signal was kept up to the peak of the first swing and then the signal was changed to velocity signal.

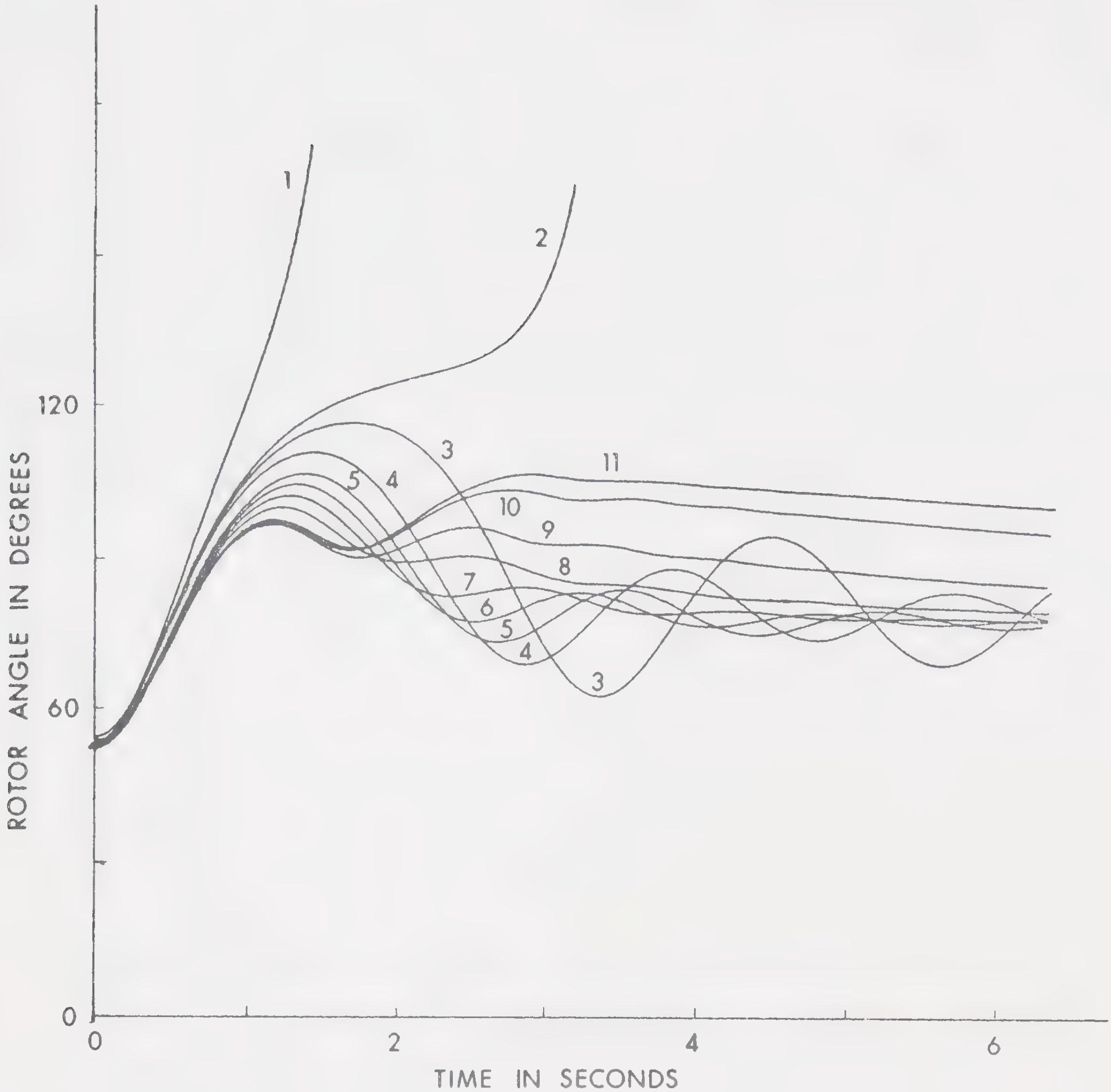


Fig. 13

Test 4 Case (i)

Effect of Different Values of Gain of Velocity Signal on Large Disturbance (0.8 p.u.)

| Curve | Signal | Curve | Signal |
|---|---|---|---|
| (1) | none | (7) | 36 $\dot{\delta}$ |
| (2) | 4 $\dot{\delta}$ | (8) | 50 $\dot{\delta}$ |
| (3) | 8 $\dot{\delta}$ | (9) | 100 $\dot{\delta}$ |
| (4) | 12 $\dot{\delta}$ | (10) | 200 $\dot{\delta}$ |
| (5) | 16 $\dot{\delta}$ | (11) | 400 $\dot{\delta}$ |
| (6) | 24 $\dot{\delta}$ | | |

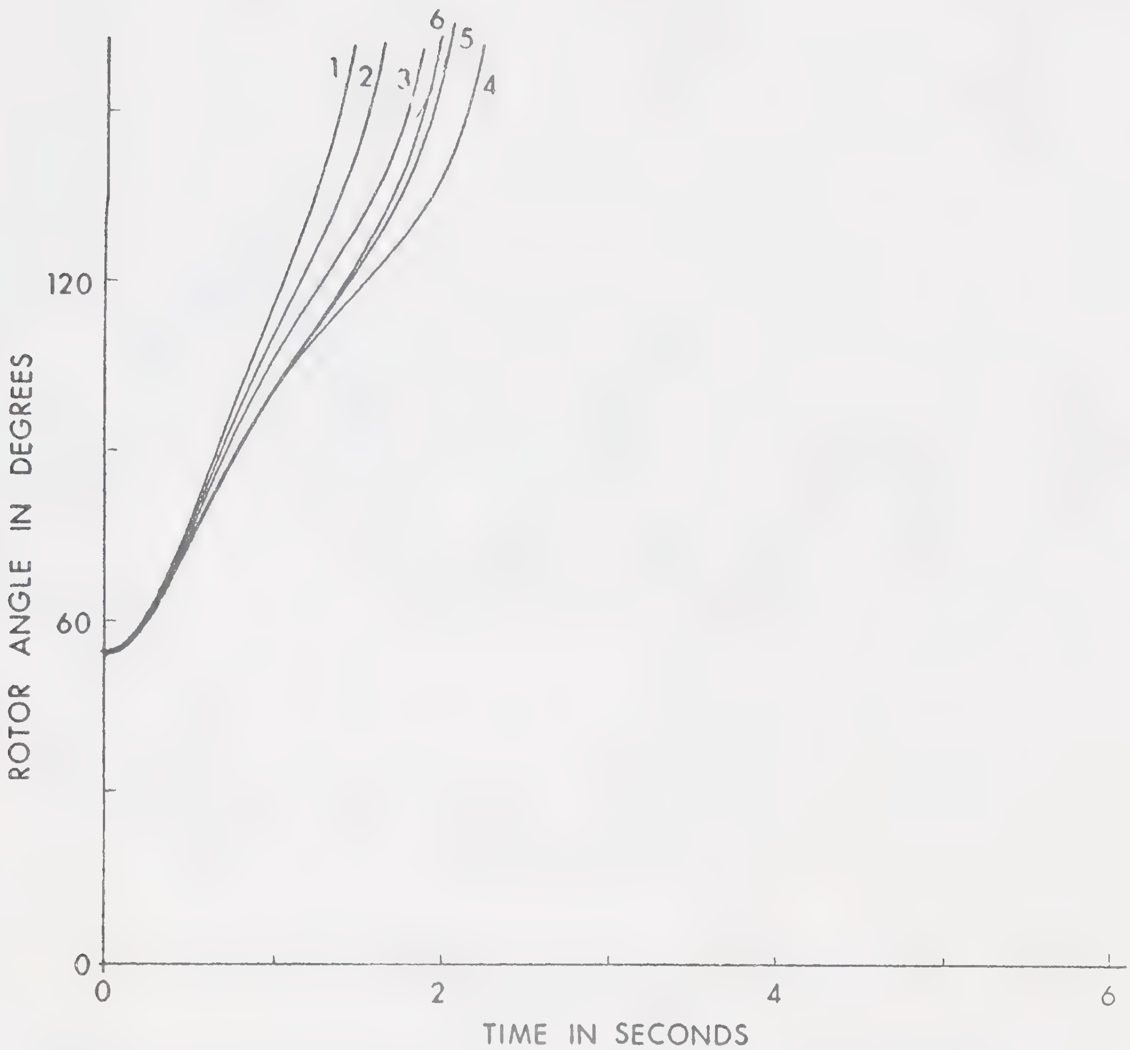


Fig. 14

Test 4 Case (ii)

Effect of Different Values of Gain of Acceleration Signal

on Large Power Disturbance (0.8 p.u.)

| Curve | Signal | Curve | Signal |
|---|---|---|---|
| (1) | none | (4) | $12\ \ddot{\delta}$ |
| (2) | $4\ \ddot{\delta}$ | (5) | $16\ \ddot{\delta}$ |
| (3) | $8\ \ddot{\delta}$ | (6) | $20\ \ddot{\delta}$ |

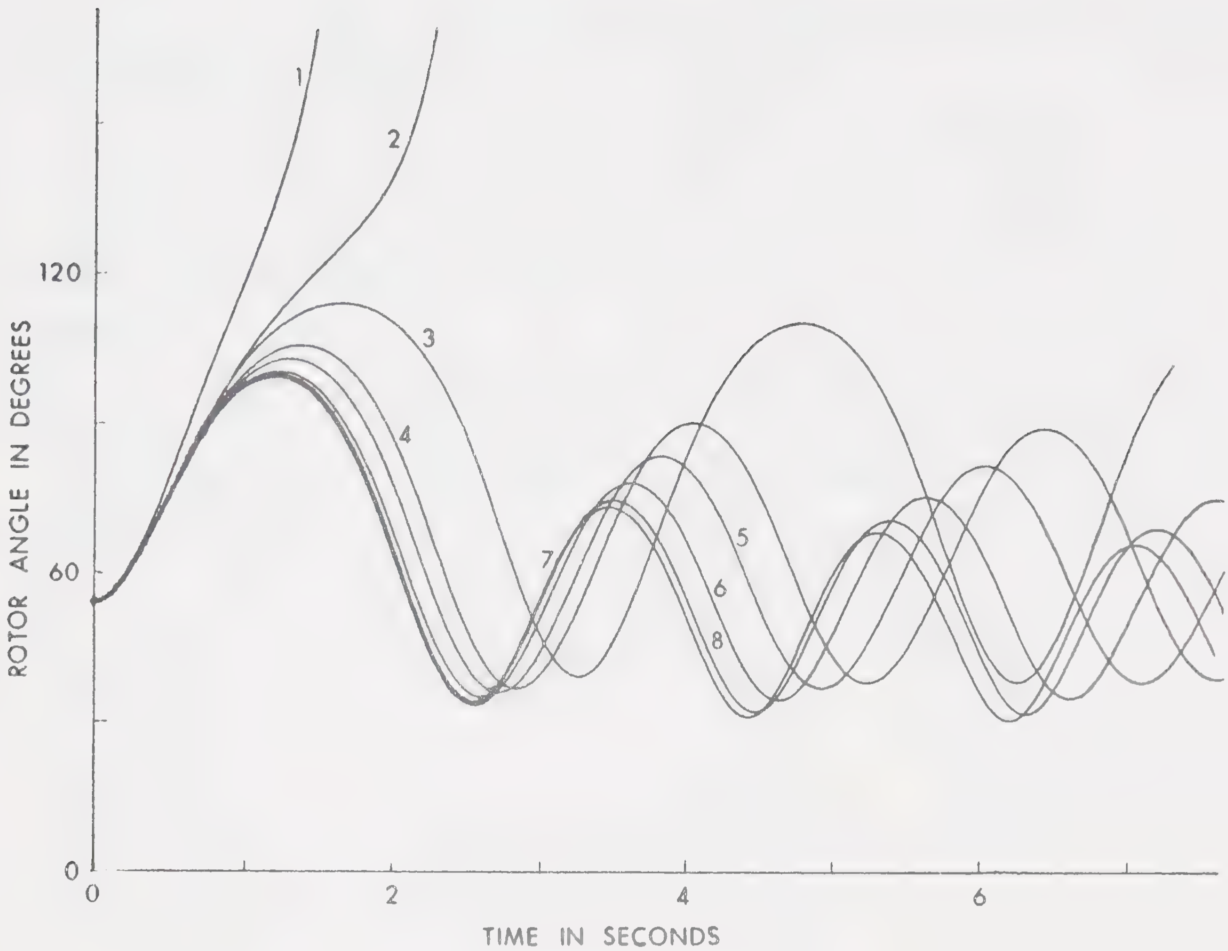


Fig. 15

Test 4 Case (iii)

Effect of Different Values of Gain of Acceleration Magnitude

Signal on Large Power Disturbance (0.8 p.u.)

| Curve | Signal | Curve | Signal |
|---|---|---|---|
| (1) | none | (6) | 50 $\lvert\ddot{\delta}\rvert$ |
| (2) | 4 $\lvert\ddot{\delta}\rvert$ | (7) | 100 $\lvert\ddot{\delta}\rvert$ |
| (3) | 8 $\lvert\ddot{\delta}\rvert$ | (8) | 130 $\lvert\ddot{\delta}\rvert$ |
| (4) | 12 $\lvert\ddot{\delta}\rvert$ | (9) | 150 $\lvert\ddot{\delta}\rvert$ |
| (5) | 24 $\lvert\ddot{\delta}\rvert$ | | |

case (ii) The effect of combining the two signals as in case (i) for small power disturbance is seen in figure 17.

The above test shows that a proper combination of the signal as in Test 5 can give better results. However, the change over requires switching through logic circuits.

Test 6

The effect of another combination signal was studied when the acceleration magnitude and velocity signals were both kept in the stabilizing circuit. This does not need any switching.

The results are given in figure 18.

| $P_e$ | $\Delta P_m$ | Signals with gain | Curves | Results |
|---|---|---|---|---|
| 1.5 | 0.8 | $8\ \dot{\delta}$ | 1 | 112° |
| 1.5 | 0.8 | $8\ \lvert\ddot{\delta}\rvert$ | 2 | 102° |
| 1.5 | 0.8 | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ | 3 | 97° |
| 1.5 | 0.8 | $4\ \dot{\delta} + 4\ \lvert\ddot{\delta}\rvert$ | 4 | 97° |
| 1.5 | 0.8 | $2\ \dot{\delta} + 6\ \lvert\ddot{\delta}\rvert$ | 5 | 99° |

The minimum value of first swing is obtained by combinations of curve 3 and 4 but curve 4 has larger oscillations on later swings. Curve 3 gives the best results.

The terminal voltage variations follow the power angle swing roughly the more damped the power angle curve the lesser are the variations in terminal voltage. The combination for curve 3 gives the least variations in voltage. Therefore, when both velocity and acceleration magnitude signals are maintained, in the composite stabilizing signal, it seems that a higher percentage of velocity signal (50 - 75 %) with lower percentage of magnitude

case (ii) The effect of combining the two signals as in i.e (1) for small power disturbance is seen in figure 17.

The above test shows that a proper combination [illegible] the signal as in Test 5 can give better results. However, t[illegible] change over requires switching through logic circuits.

Test 6

The effect of another combination signal was [illegible]tied when the acceleration magnitude and velocity signals wer[illegible] [illegible]oth kept in the stabilizing circuit. This does not need any [illegible]itching.

The results are g[illegible]ven in figure 18.

| $P_e$ | $\Delta P_m$ | Signals with gain | Curves | Results |
|---|---|---|---|---|
| 1.5 | 0,8 | 8 5 [illegible] | 1 | 11[illegible] |
| 1.5 | 0.8 | 8 [illegible] | 2 | 10[illegible] |
| 1.5 | 0.8 | [illegible] | 3 | [illegible] |
| 1.5 | 0.8 | [illegible] | 4 | [illegible] |
| 1.5 | 0.8 | [illegible] | [illegible] | [illegible] |

[illegible]

combinations of [illegible]urve 2 and [illegible] [illegible] curve 4 has larger oscillations on later swings. Curve 3 g[illegible]es [illegible]he best results.

The terminal vo[illegible]age [illegible]ariations follow the power angle swing roughly the more da[illegible]ed [illegible] power angle curve the lesser are the variations in terminal voltage. The combination for curve 3 gives the least variations in voltage. Therefore, when both velocity and acceleration magnitude signals are maintained, in the composite stabilizing signal, it seems that a higher percentage of velocity signal (50 - 75 %) with lower percentage of magnitude

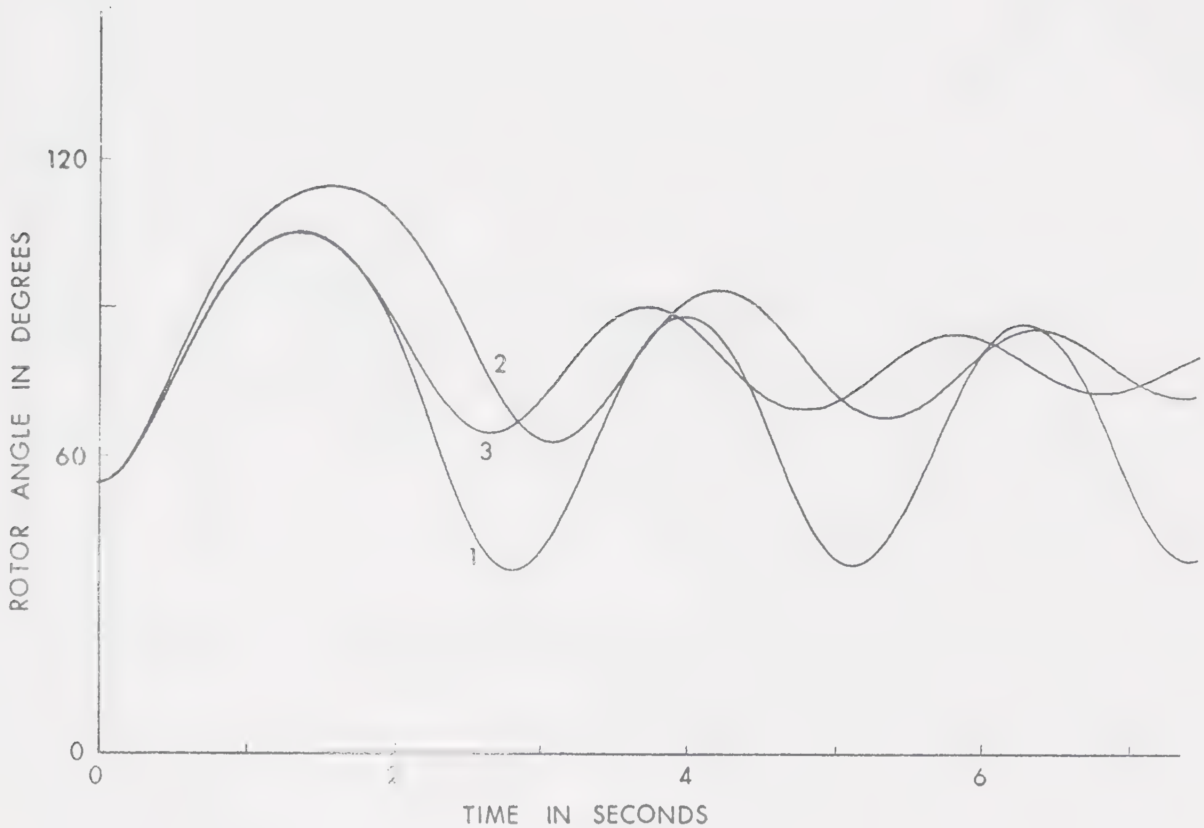


Fig. 16

Test 5 Case (i)

Effect of Combining Acceleration Magnitude Signal

and Velocity Signal on Large Power Disturbance 0.8 p.u.

(1) with acceleration magnitude signal

(2) with velocity signal

(3) with acceleration magnitude signal maintained only up to first peak then switched to velocity signal

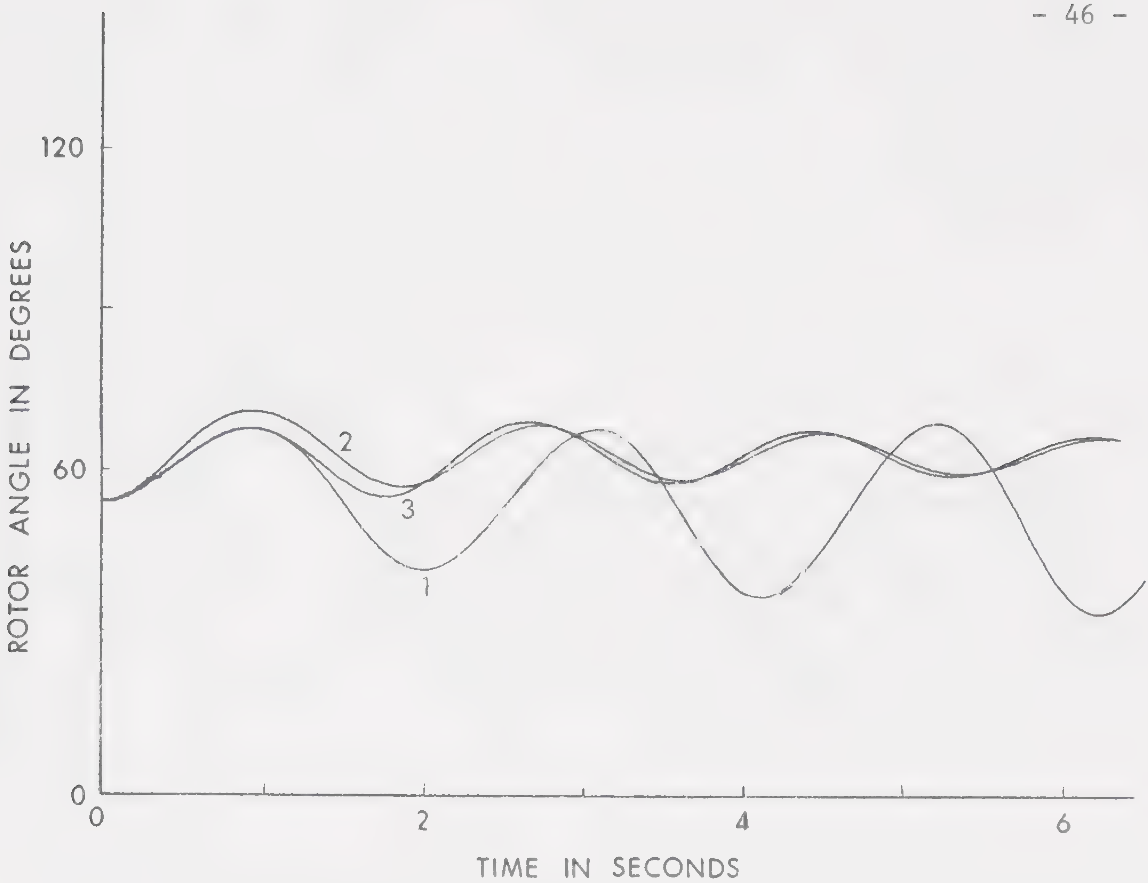


Fig. 17

Test 5 Case (ii)

Effect of Combining Acceleration Magnitude and Velocity Signals on Small Power Disturbance

(1) with acceleration magnitude signal

(2) with velocity signal

(3) with acceleration magnitude signal maintained up to first peak and then switched to velocity signal

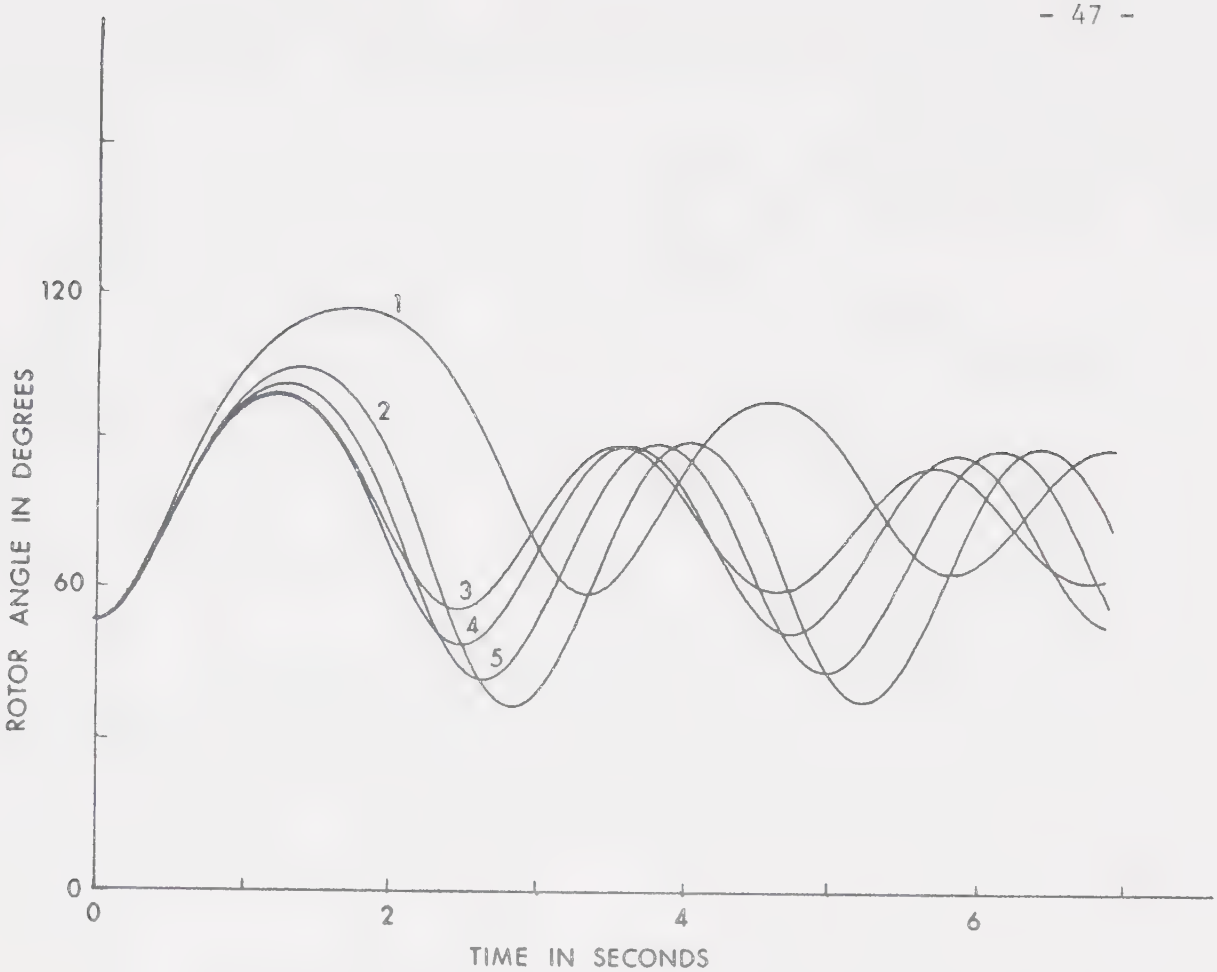


Fig. 18

Test 6

Effect of Combination Signals on Large Power Disturbance

| Curve | Signal |
| --- | --- |
| (1) | $8\ \dot{\delta}$ |
| (2) | $8\ \lvert\ddot{\delta}\rvert$ |
| (3) | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ |
| (4) | $4\ \dot{\delta} + 4\ \lvert\ddot{\delta}\rvert$ |
| (5) | $2\ \dot{\delta} + 6\ \lvert\ddot{\delta}\rvert$ |

signal (50 - 25 % ) can give better results.

Test 7

A small disturbance of 0.4 $P_m$ was imposed and the effect of the combination signal was observed (fig. 19 )

| $P_e$ | $\Delta P_m$ | Signal | Curves | Remarks |
|---|---|---|---|---|
| 1.5 | 0.4 | no signal | 1 | growing oscillation |
| 1.5 | 0.4 | $6\ \dot{\delta}$ | 2 | damped |
| 1.5 | 0.4 | $8\ \dot{\delta}$ | 3 | first peak reduced |
| 1.5 | 0.4 | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ | 4 | response improved further |

For a small disturbance it appears that although velocity signal alone may damp the oscillation, the combination signal can improve upon the first swing as well as the damping of later oscillations.

Test 8

A typical case of loss of line was simulated and effect of the velocity, magnitude and combination signal was found on the disturbance.

case (i) This disturbance amounts to losing one line out of the two parallel ties which means the loss of 50% of the power line capacity. (Fig. 20)

| $P_e$ | Signal | Curve | Remarks |
|---|---|---|---|
| 1.5 | $8\ \dot{\delta}$ | 1 | first swing |
| 1.5 | $8\ \lvert\ddot{\delta}\rvert$ | 2 | - same |
| 1.5 | $4\ \dot{\delta} + 4\ \lvert\ddot{\delta}\rvert$ | 3 | reduced by 5% |
| 1.5 | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ | 4 | same as 3 but later oscillations reduced |

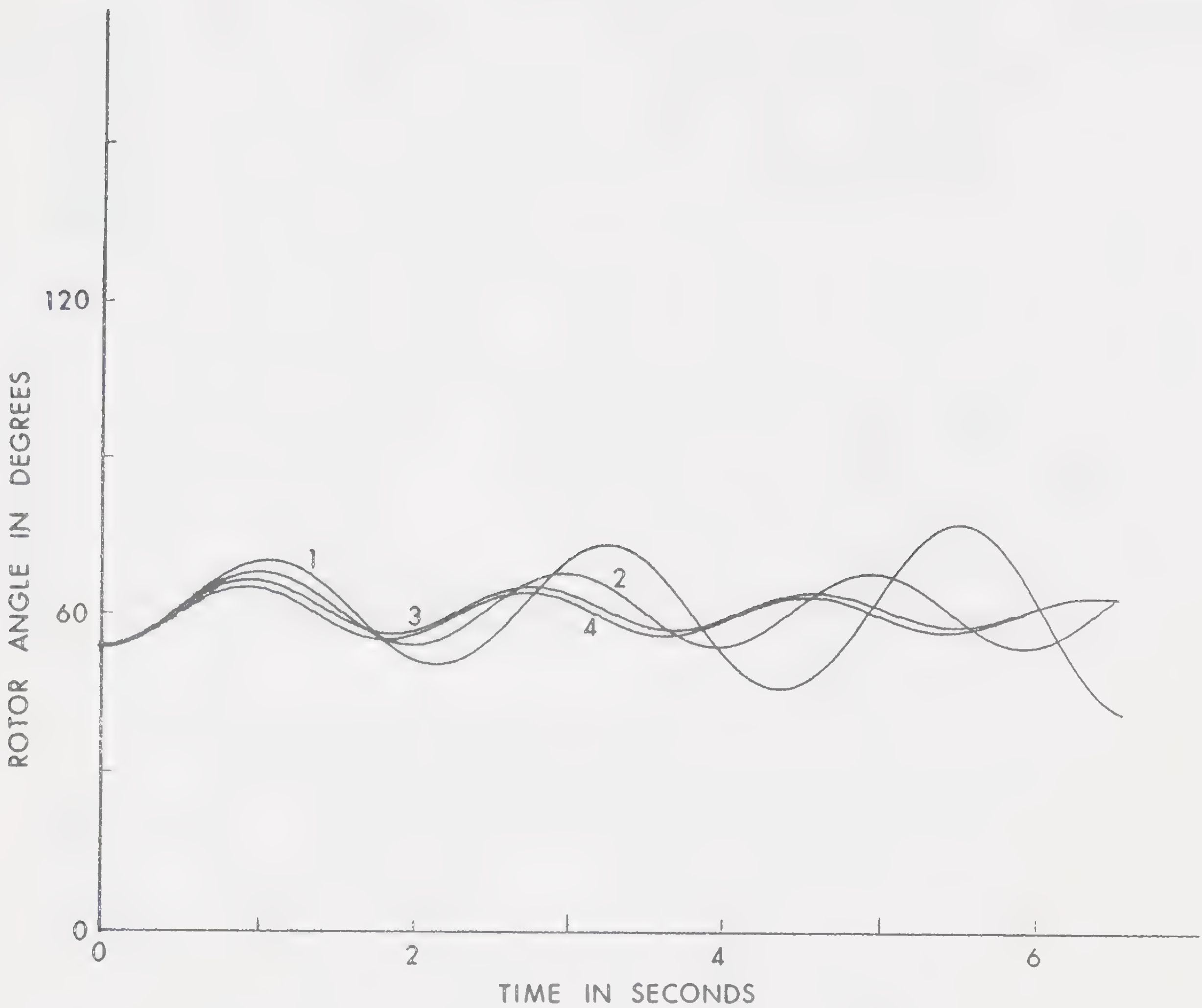


Fig. 19

Test 7

Effect of Combination Signals on Small Power Disturbance (0.4 p.u.)

| Curve | Signal |
|---|---|
| (1) | none |
| (2) | $6\ \dot{\delta}$ |
| (3) | $8\ \dot{\delta}$ |
| (4) | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ |

This being a very large swing the effect of magnitude signal is not felt prominently as can be seen in case (ii).

case (ii) The disturbance amounts to losing one line out of three parallel ties which is equivalent to losing 33% line capacity. (Fig. 21)

| $P_e$ | Signal | Curve | Remarks |
|---|---|---|---|
| 1.5 | $8\ \dot{\delta}$ | 1 | |
| 1.5 | $8\ \lvert\ddot{\delta}\rvert$ | 2 | first swing same as in 1 |
| 1.5 | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ | 3 | first peak reduced by 10% |
| 1.5 | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ ($\lvert\ddot{\delta}\rvert$ signal switched off after first peak) | 4 | second peak higher than in 3 |

Test 9

As in test 8 the case studied represents loss of 50% of line capacity. In this test we observe the effects of various values of gain of the signals. In case (iv) effects of a few combination signals are studied.

case (i) The gain for the acceleration magnitude signal is increased in steps. It is seen from fig. (22) that,

1) With increasing values of gain the system is driven towards stable conditions. The value of 10 is just sufficient in this case to make the system stable.

2) Increasing values of gain reduces the first peak. However, increasing gain beyond 20 has the adverse effect as is seen by curve 7 with gain of 30.

case (ii) The same is repeated to study effects of various values of gain of the acceleration signal. The signal gain when increased

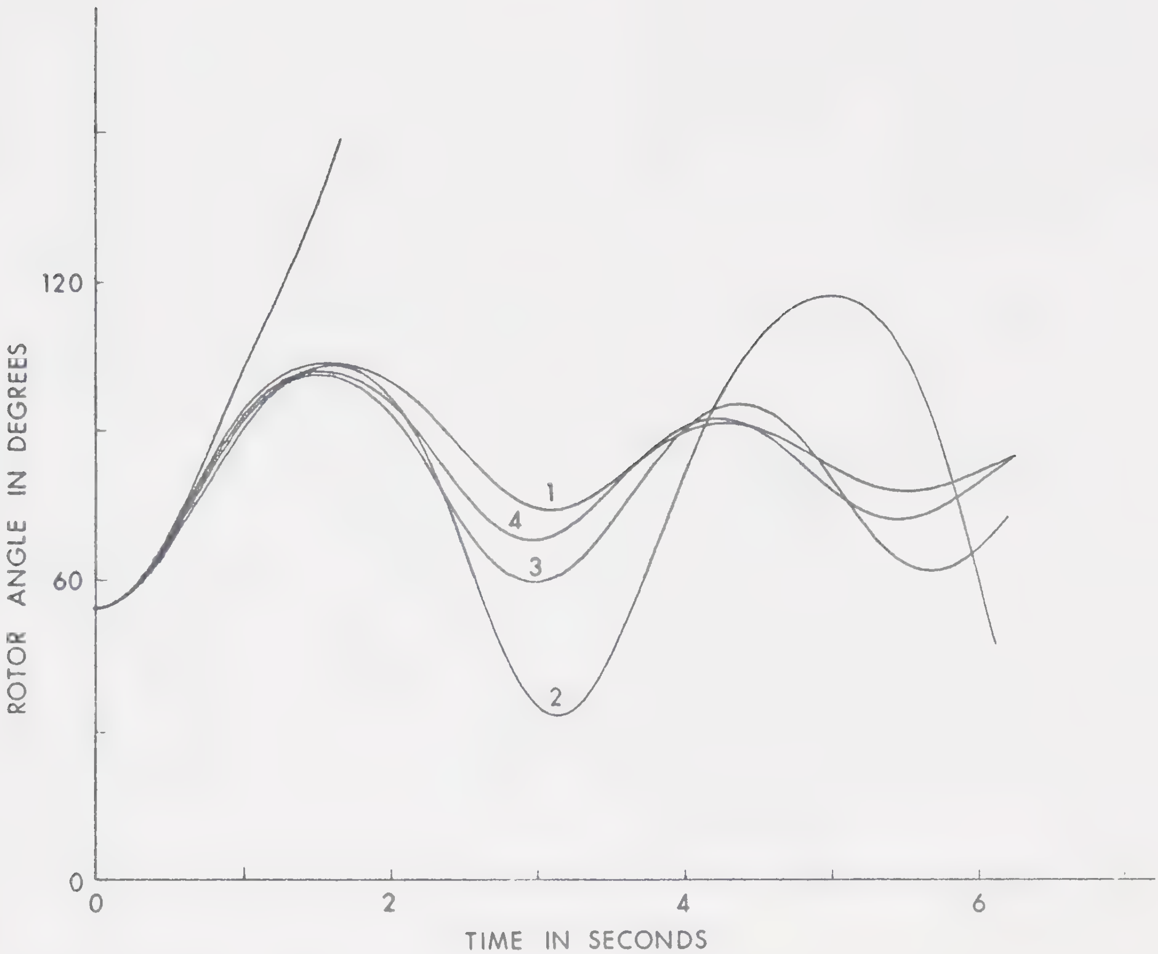


Fig. 20

Test 8 Case (i)

Effect of Combination Signals on Loss of Line (losing 50% line capacity)

| Curve | Signal |
|---|---|
| (1) | $8\ \dot{\delta}$ |
| (2) | $8\ \lvert\ddot{\delta}\rvert$ |
| (3) | $4\ \dot{\delta} + 4\ \lvert\ddot{\delta}\rvert$ |
| (4) | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ |

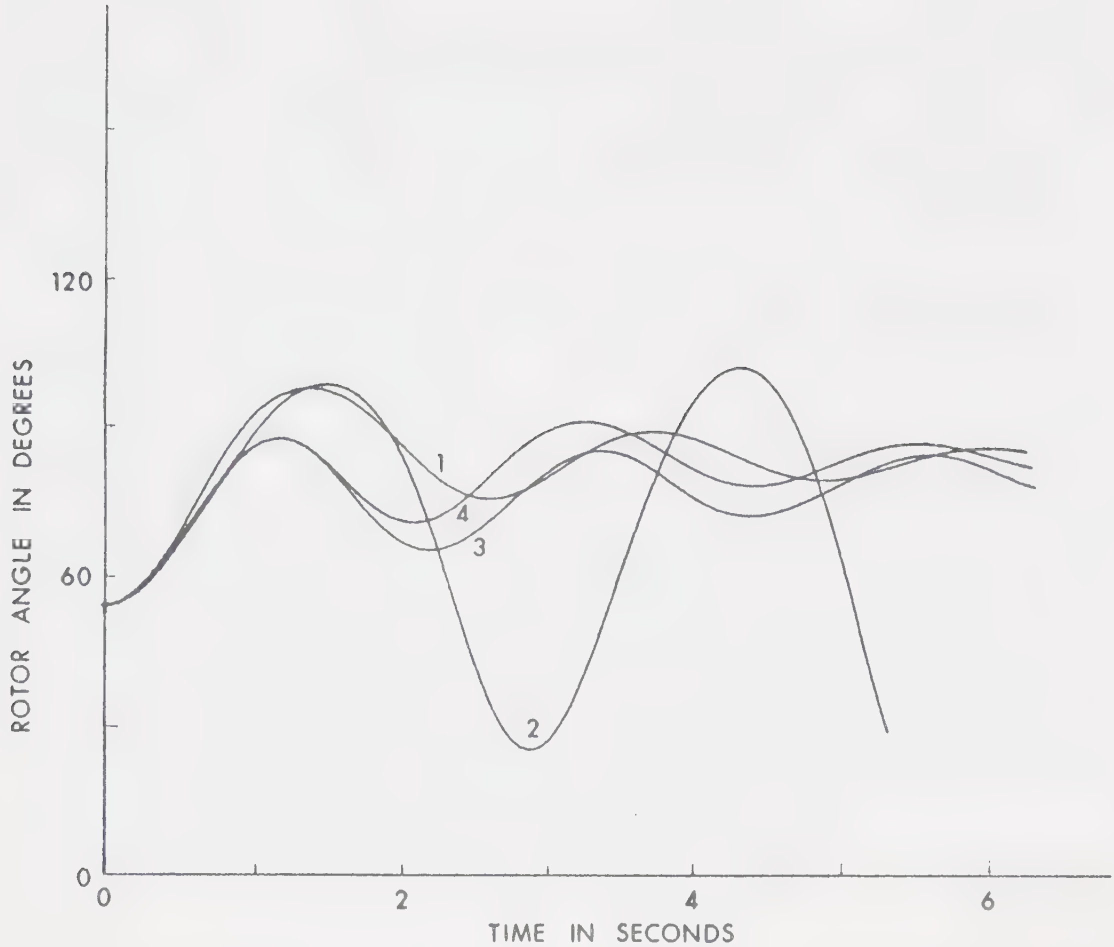


Fig. 21

Test 8 Case (ii)

Effect of Combination Signals on Loss of Line (losing 33% line capacity)

| Curve | Signal |
|---|---|
| (1) | $8\ \dot{\delta}$ |
| (2) | $8\ \lvert\ddot{\delta}\rvert$ |
| (3) | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ |
| (4) | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ - but $\lvert\ddot{\delta}\rvert$ signal switched off after 1st peak |

tries to slow down the system but is unable to arrest the first peak which is seen from curves 1 to 7 of fig. (23). Further increase beyond value of 16 shows adverse effect as seen from curve 8.

The acceleration signal, as observed in earlier cases also, does not show promise.

case (iii) This case indicates the effect of gain of velocity error signal. Increasing values of gain increases damping as well as reduces the first peak as seen from fig. (24).

case (iv) This case is a more interesting one which shows in fig. (25) that a combination of velocity error and acceleration magnitude signals gives better results than could be attained with the same values of gains if pure signals were used.

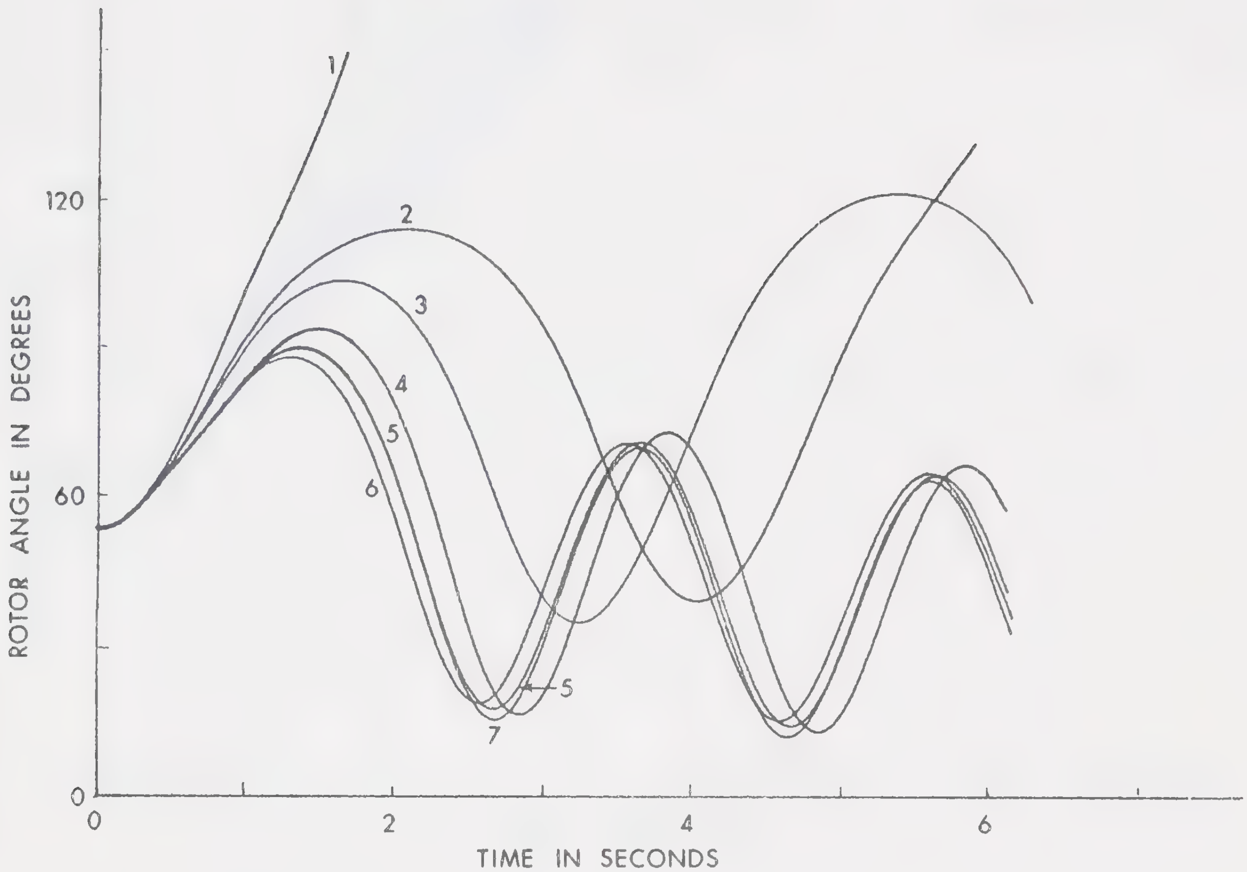


Fig. 22

Test 9 Case (i)

Effect of Different Values of Gain of Acceleration Magnitude

Signal on Loss of 50% Line Capacity

| Curve | Signal | Curve | Signal |
|---|---|---|---|
| (1) | none | (5) | $14\ \lvert\ddot{\delta}\rvert$ |
| (2) | $6\ \lvert\ddot{\delta}\rvert$ | (6) | $20\ \lvert\ddot{\delta}\rvert$ |
| (3) | $8\ \lvert\ddot{\delta}\rvert$ | (7) | $30\ \lvert\ddot{\delta}\rvert$ |
| (4) | $10\ \lvert\ddot{\delta}\rvert$ | | |

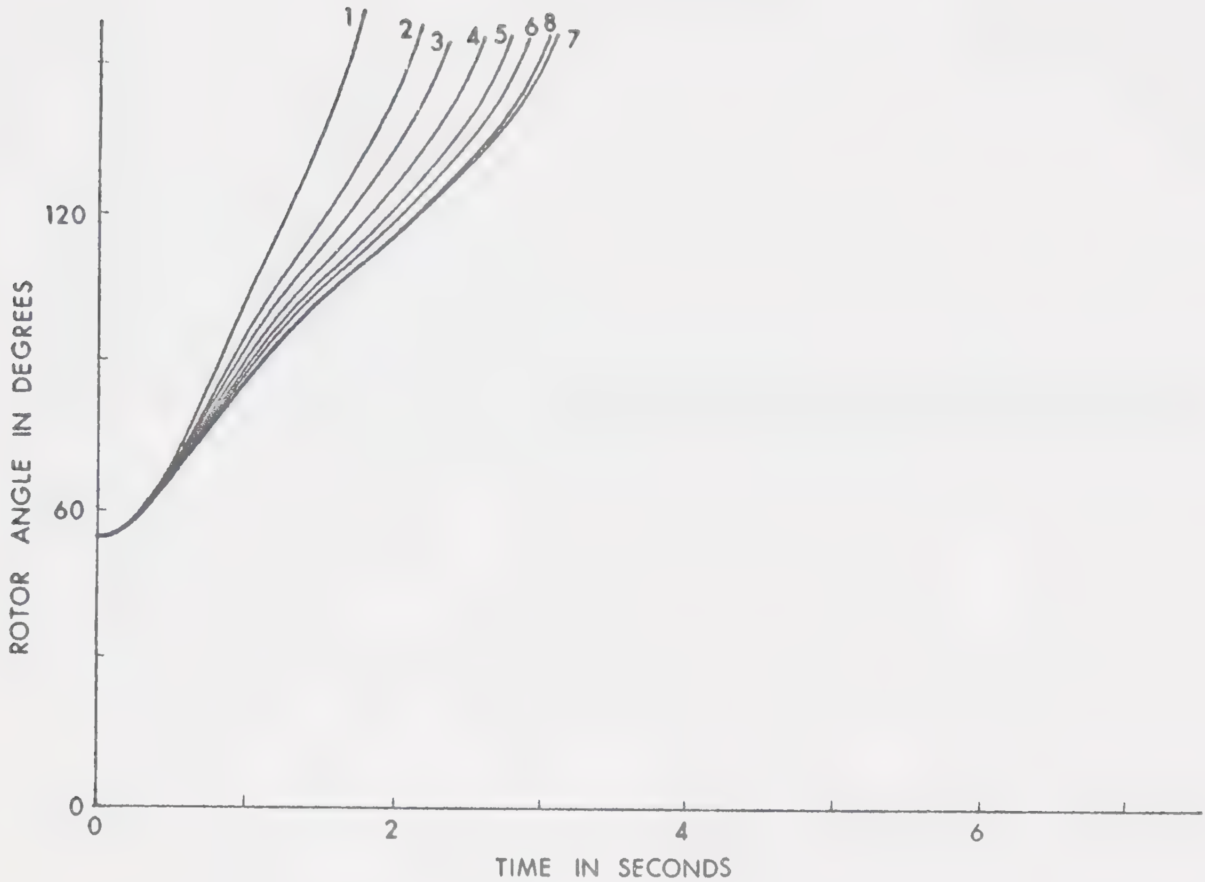


Fig. 23

Test 9 Case (ii)

Effect of Different Values of Gain of Acceleration Signal

on Loss of 50% Line Capacity

| Curve | Signal | Curve | Signal |
|---|---|---|---|
| (1) | none | (5) | $10\ \ddot{\delta}$ |
| (2) | $4\ \ddot{\delta}$ | (6) | $12\ \ddot{\delta}$ |
| (3) | $6\ \ddot{\delta}$ | (7) | $16\ \ddot{\delta}$ |
| (4) | $8\ \ddot{\delta}$ | (8) | $20\ \ddot{\delta}$ |

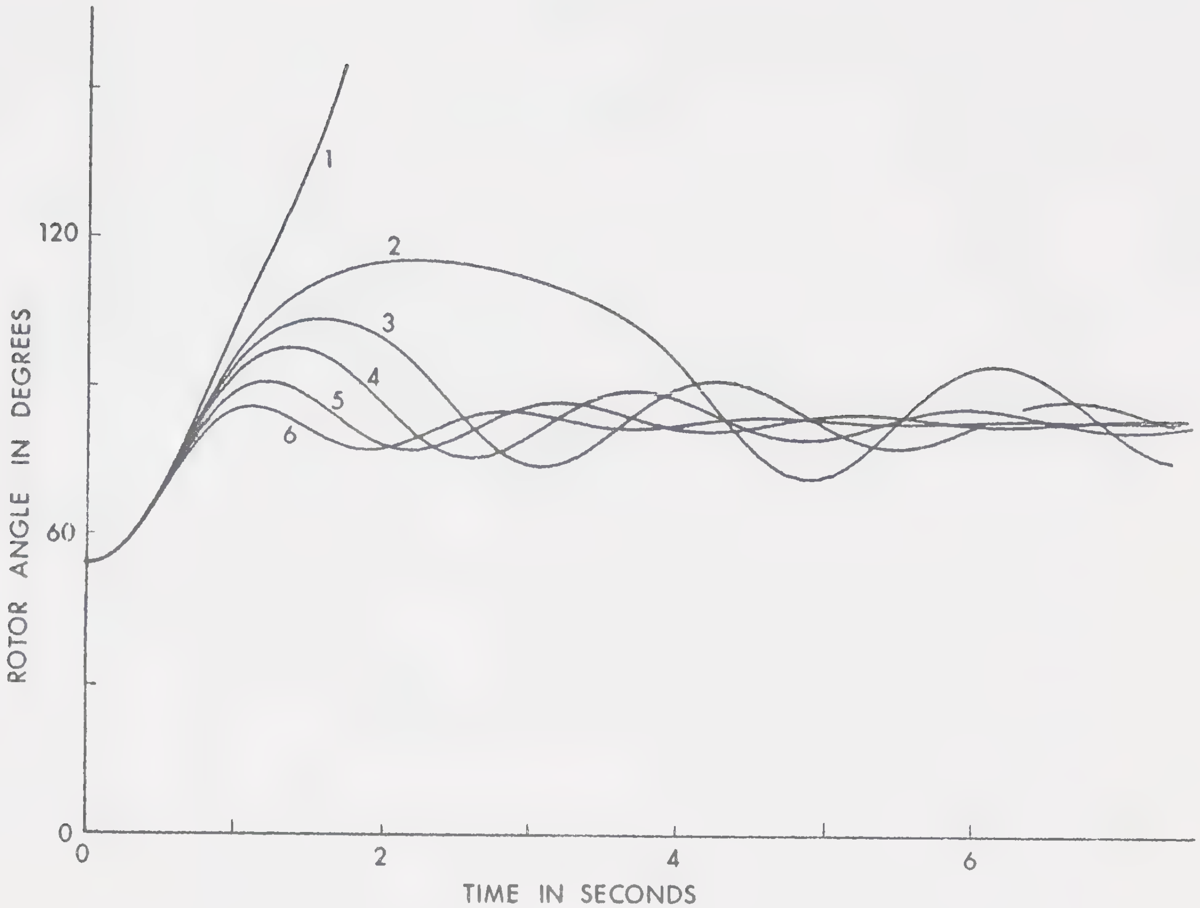


Fig. 24

Test 9 Case (iii)

Effect of Different Values of Gain of Velocity Signal

on Loss of 50% Line Capacity

| Curve | Signal |
| --- | --- |
| (1) | none |
| (2) | $6\ \dot{\delta}$ |
| (3) | $10\ \dot{\delta}$ |
| (4) | $14\ \dot{\delta}$ |
| (5) | $20\ \dot{\delta}$ |
| (6) | $30\ \dot{\delta}$ |

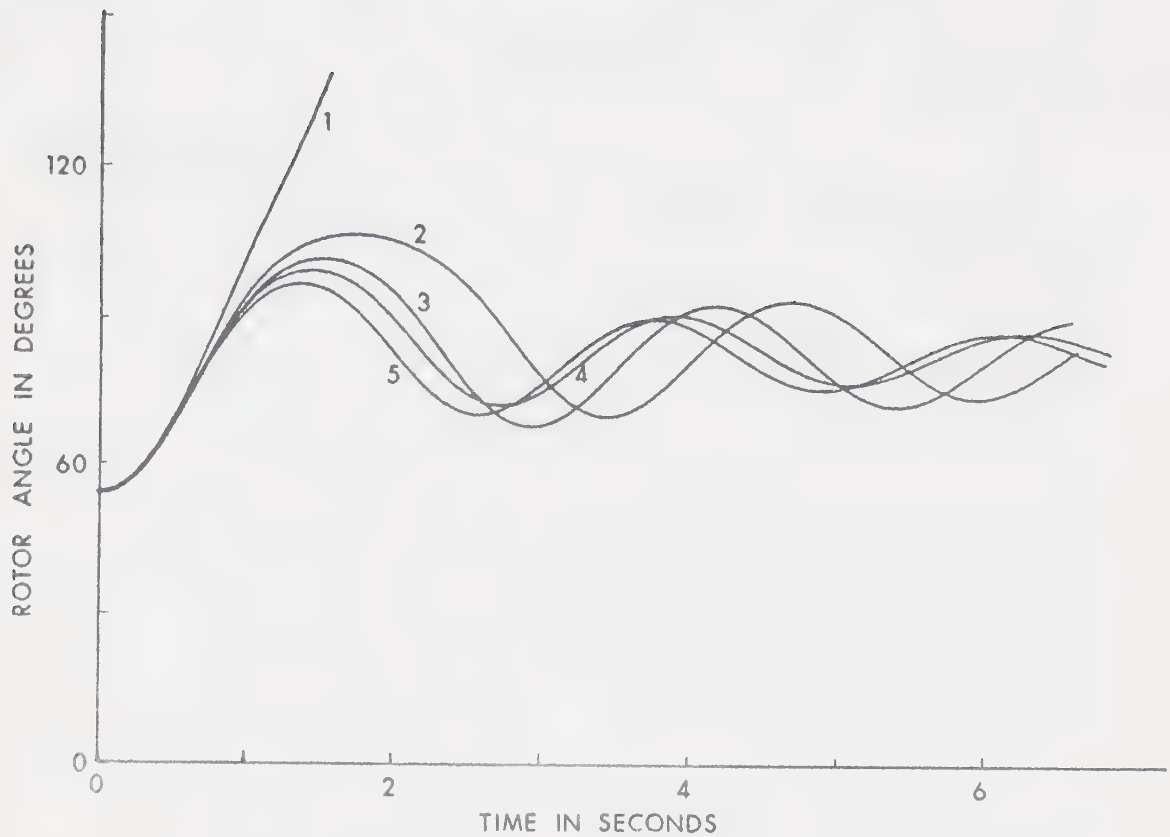


Fig. 25

Test 9 Case (iv)

Effect of Different Combination Signals on Loss of 50% Line Capacity

| Curve | Signal |
|---|---|
| (1) | none |
| (2) | $6\ \dot{\delta} + \lvert\ddot{\delta}\rvert$ |
| (3) | $6\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ |
| (4) | $8\ \dot{\delta} + \lvert\ddot{\delta}\rvert$ |
| (5) | $8\ \dot{\delta} + 2\ \lvert\ddot{\delta}\rvert$ |

# CHAPTER VI

# CONCLUSIONS

## Large Oscillations

1. The stability in general depends on the first power oscillation. On large power swings where the velocity signal may not be capable of arresting the instability the acceleration magnitude signal of equivalent gain may be able to stabilize the system.
2. The velocity signal is essential to provide sufficient damping torque to damp out the oscillations.
3. The acceleration signal alone is detrimental to the stability.
4. The acceleration magnitude signal is found effective in reducing the first swing peak. However, it adds to the magnitude of the later oscillations.
5. A combination of velocity signal and acceleration magnitude signal can give optimum effects.

## Small Oscillations

The above also holds for small oscillations. Though as the power deviation is small it seems that only the velocity signal can do the job. However, if an acceleration magnitude signal is incorporated in the stabilizing circuit, effects can be observed in reduction of the first swing.

Other Considerations in Design of the Stabilizing Signals

In practice difficulty arises in deriving a proportional velocity signal. The speed signal is obtained from the output of a tacho-generator which may have an inherent time lag. For this signal to be useful in stabilizing system response the time constant must be very low i.e. of the order of 0.1 second. In practice a lead-lag circuit may be necessary to obtain the same. The velocity signal thus obtained must also be able to account for the fact that the steady state velocity does vary about its nominal value under normal load changes.

A similar situation may arise in case of an acceleration signal due to the time constant of the transducers used, with the exception that no reset is necessary as $\ddot{\delta}$ is 0 in steady state.

Further studies on stabilizing signals and their influence on stability performance can be extended to a multimachine case, including the optimization of control signals. This may not seem feasible on an analogue computer and therefore a digital computer may be required to study the problem.

The above study has tried to show the merits of various signals only. However, an optimization of a stabilizing scheme suited to a particular system can be achieved only after a detailed study taking into account other practical considerations.

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## LIST OF SYMBOLS

| | | |
|---|---|---|
| $v_f$ | = | applied field voltage |
| $v_d$ | = | direct axis terminal voltage |
| $v_q$ | = | quadrature axis terminal voltage |
| $v_{kd}$ | = | direct axis amortisseur voltage |
| $v_{kq}$ | = | quadrature axis amortisseur voltage |
| $r_f$ | = | field resistance |
| $r_a$ | = | armature resistance |
| $r_{kd}$ | = | amortisseur direct axis resistance |
| $r_{kq}$ | = | amortisseur quadrature axis resistance |
| $x_f$ | = | direct axis field reactance |
| $x_d$ | = | direct axis armature reactance |
| $x_q$ | = | quadrature axis armature reactance |
| $x_{kd}$ | = | direct axis amortisseur reactance |
| $x_{kq}$ | = | quadrature axis amortisseur reactance |
| $x_{md}$ | = | direct axis mutual reactance |
| $x_{ad}$ | = | direct axis mutual reactance |
| $x_{mq}$ | = | quadrature axis mutual reactance |
| $x_{aq}$ | = | quadrature axis mutual reactance |
| $x_{akd}$ | = | direct axis mutual reactance between armature and amortisseur |
| $x_{akq}$ | = | quadrature axis mutual reactance between armature and amortisseur |
| $x_{afd}$ | = | direct axis mutual reactance between armature and field. |

$x_{fdd}$ = direct axis mutual reactance between armature and field

$x_{fkd}$ = direct axis mutual reactance between amortisseur and field

$x_{al}$ = armature leakage reactance

$x_L$ = line reactance

$\psi_f$ = field flux linkage

$\psi_d$ = direct axis armature flux linkage

$\psi_q$ = quadrature axis armature flux linkage

$\psi_{kd}$ = direct axis amortisseur flux linkage

$\psi_{kq}$ = quadrature axis amortisseur flux linkage

$\omega_o$ = synchronous speed in radians per second

$p$ = differential operator

$M$ = angular momentum in mega-joules

$H$ = inertia constant

$\delta$ = rotor displacement angle

$\theta$ = power factor angle

$T$ = machine torque

$T_a$ = accelerating torque on rotor

$T_e$ = electrical torque developed

$T_m$ = mechanical torque input

$P_a$ = accelerating power on rotor

$P_e$ = electrical power developed

$P_m$ = mechanical power input

| | | |
|---|---|---|
| $\alpha$ | = | angular acceleration |
| $D$ | = | dissipation or damping factor |
| $v_t$ | = | machine terminal voltage |
| $i_f$ | = | field current |
| $i_d$ | = | direct axis armature current |
| $i_q$ | = | quadrature axis armature current |
| $i_{kd}$ | = | direct axis amortisseur current |
| $i_{kq}$ | = | quadrature axis amortisseur current |
| $e$ | = | voltage at the infinite bus |
| $\dot{\delta}$ | = | rotor angular velocity |
| $\ddot{\delta}$ | = | rotor angular acceleration |
| $\dot{\delta}$ signal | = | velocity error signal or proportional velocity signal or velocity signal |
| $\ddot{\delta}$ signal | = | acceleration signal or proportional acceleration signal |
| $\lvert\ddot{\delta}\rvert$ signal | = | acceleration magnitude signal or proportional acceleration magnitude signal |

# APPENDIX I

## Parameters

All values in per unit

| | |
|---|---|
| rating | 1 p.u. |
| speed | 377 rad. per sec. |
| inertia constant H | 3 |
| $x_1$ | 0.13 |
| $x_d$ | 0.68 |
| $x_f$ | 0.692 |
| $x_q$ | 0.438 |
| $x_{kd}$ | 0.695 |
| $x_{kq}$ | 0.468 |
| $x_{aq}$ | 0.318 |
| $x_{ad}$ | 0.562 |

# APPENDIX II

## Scaled Equation

Machine Equation

$$\left[\frac{\psi_f}{10}\right] = \left[\frac{v_f}{10}\right] - \left[\frac{i_f}{10}\right] r_f$$

$$\left[\frac{\psi_d}{10}\right] = \left[\frac{v_d}{10}\right] + \left[\frac{i_d}{10}\right] r + \left[\frac{\psi_a}{10}\right] \omega$$

$$\left[\frac{\psi_{kd}}{\omega}\right] = - \left[\frac{i_{kd}}{10}\right] r_{kd}$$

$$\left[\frac{\psi_q}{10}\right] = \left[\frac{v_q}{10}\right] + \left[\frac{i_q}{10}\right] r - \left[\frac{\psi_d}{10}\right] \omega$$

$$\left[\frac{\psi_{kq}}{10}\right] = \left[\frac{i_{kq}}{10}\right] r_{kq}$$

$\omega$ = 1 p.u. = 377 rad/sec

$$\left[\frac{i_f}{10}\right] = 5.34 \left[\frac{\psi_f}{10}\right] - 2.54 \left[\frac{\psi_d}{10}\right] - 2.26 \left[\frac{\psi_{kd}}{10}\right]$$

$$\left[\frac{i_d}{10}\right] = 2.54 \left[\frac{\psi_f}{10}\right] - 2.58 \left[\frac{\psi_d}{10}\right] + 2.45 \left[\frac{\psi_{kd}}{10}\right]$$

$$\left[\frac{i_{kd}}{10}\right] = -2.26 \left[\frac{\psi_f}{10}\right] - 2.45 \left[\frac{\psi_d}{10}\right] + 5.23 \left[\frac{\psi_{kd}}{10}\right]$$

$$\left[\frac{i_q}{10}\right] = -4.52 \left[\frac{\psi_q}{10}\right] + 3.09 \left[\frac{\psi_{kq}}{10}\right]$$

$$\left[\frac{i_{kq}}{10}\right] = -3.09 \left[\frac{\psi_q}{10}\right] + 4.25 \left[\frac{\psi_{kq}}{10}\right]$$

Swing Equation

$$\left[\frac{\ddot{\delta}}{100}\right] = -D \left[\frac{\dot{\delta}}{100}\right] + 0.0166 \left[\frac{P_a}{100}\right]$$

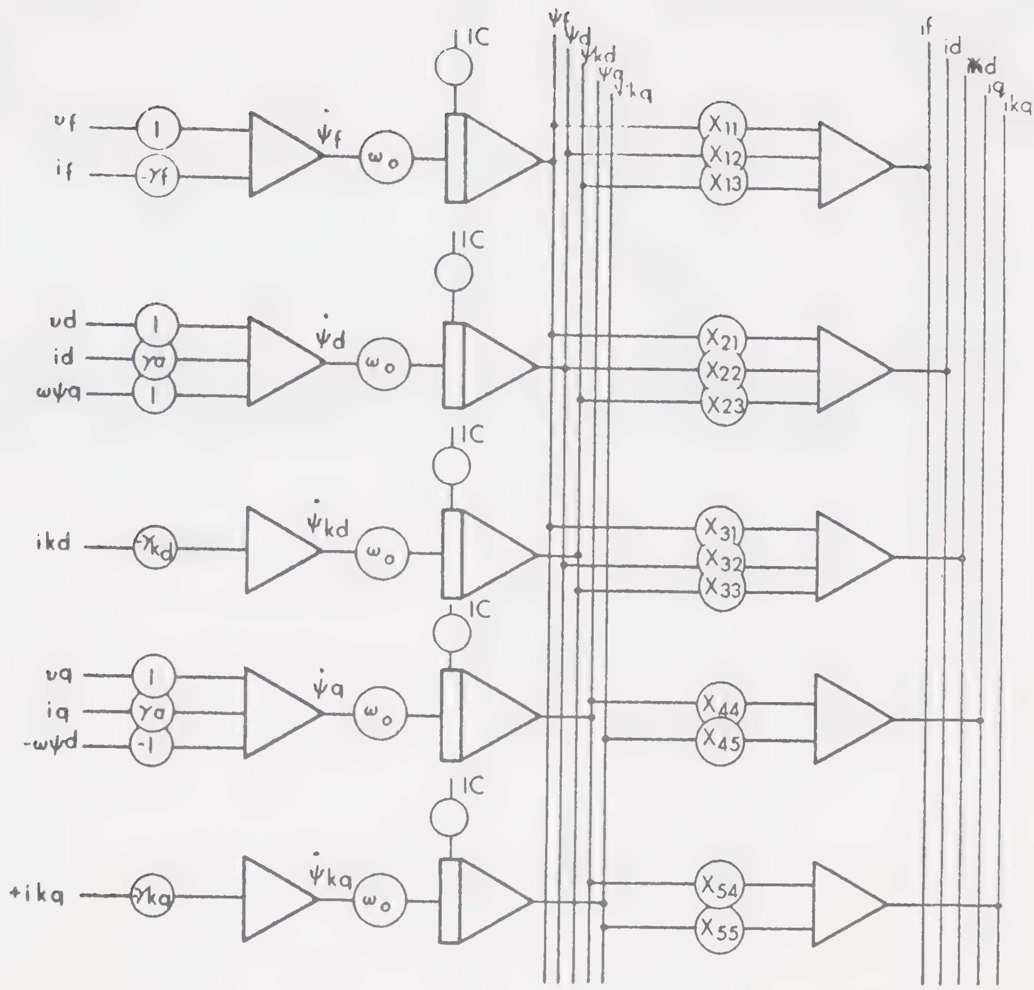


Fig. AII-1

Analogue Computer Diagram for

Synchronous Machine

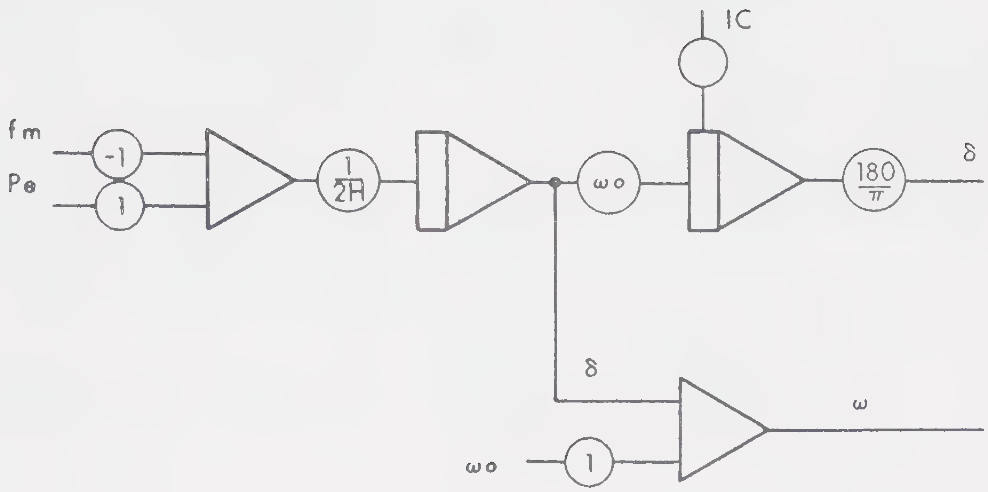


Fig. AII-2

Analogue Computer Diagram to

Represent Swing Equation

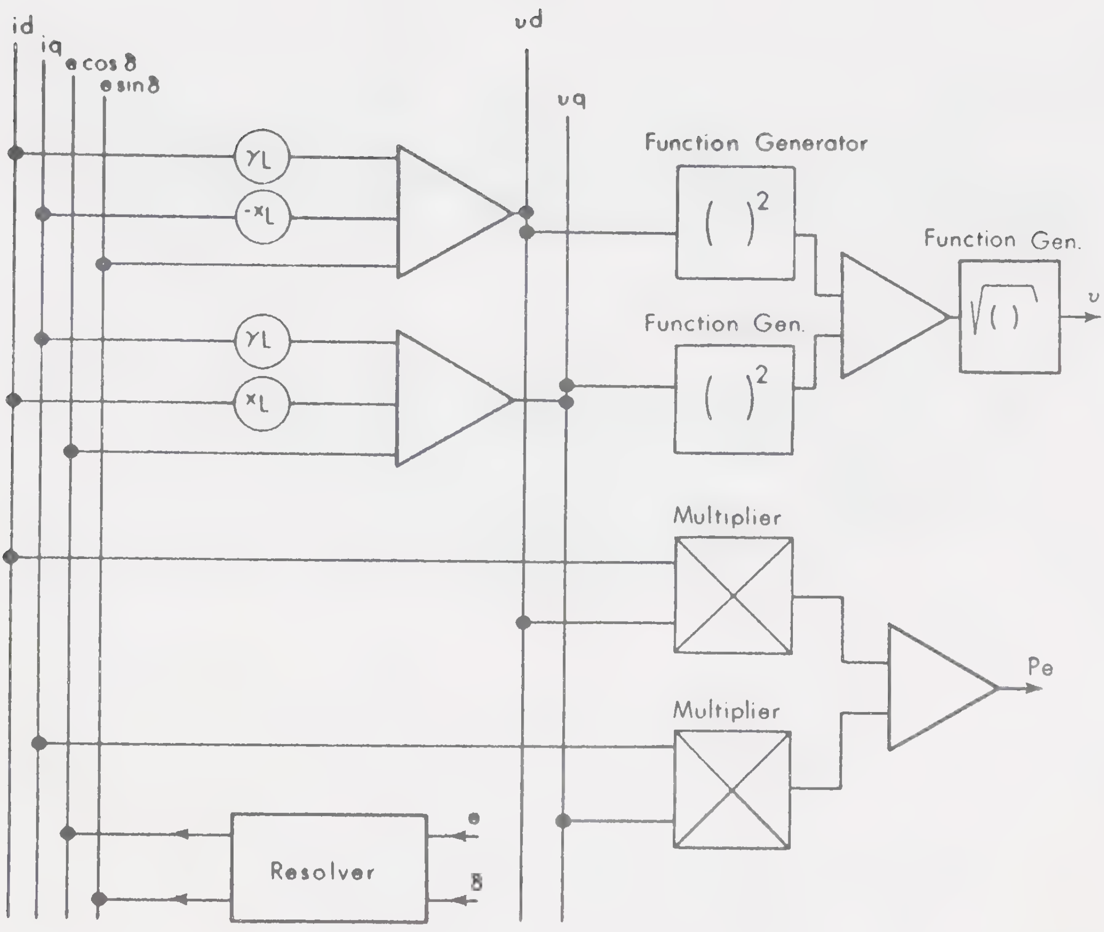


Fig. AII-3

Analogue Computer Diagram to Represent

Machine Bus and Line

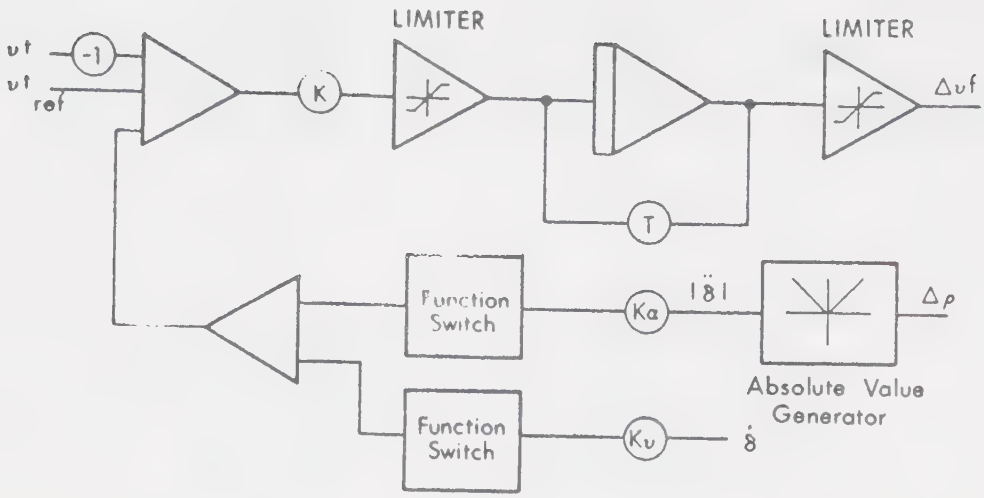


Fig. AII-4

Analogue Computer Diagram to Represent

Automatic Voltage Regulator with

Stabilizing Signals

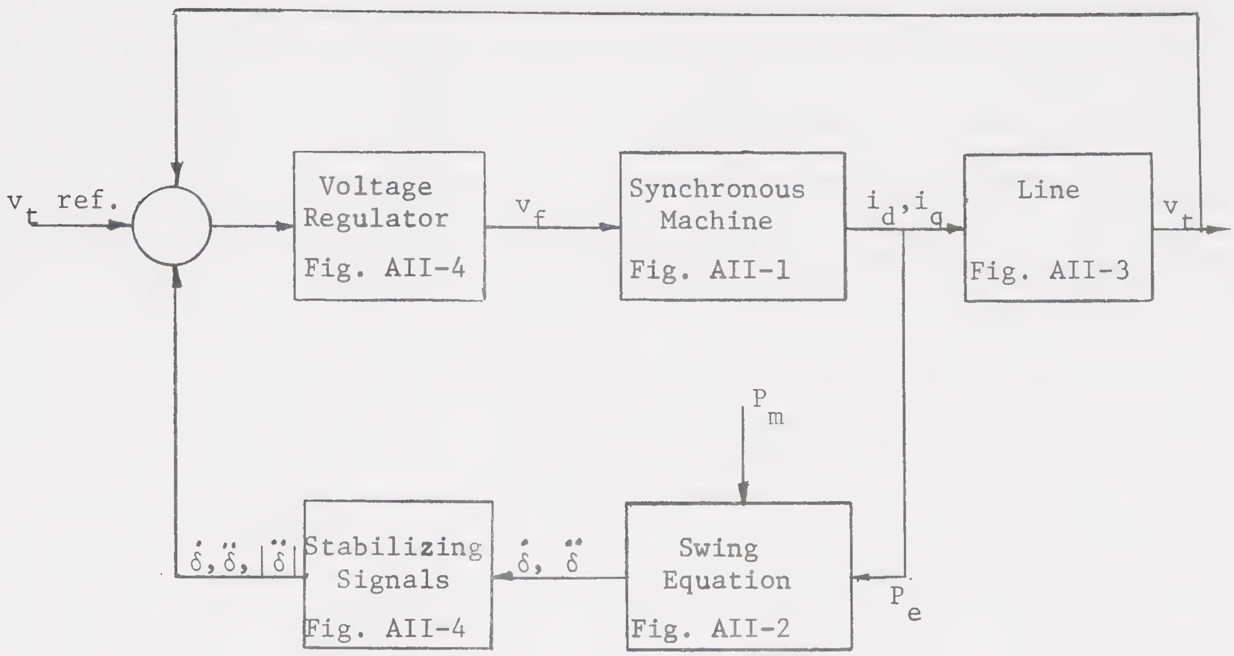


Fig. A II-5

Schematic block diagram

of the system studied